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National Aeronautics and Space Administration

heliophysics

Our Dynamic Space Environment:

Heliophysics Science and Technology Roadmap for 2014-2033

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2014 Heliophysics Roadmap Team

Heliophysics Roadmap Subpanel:
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Dr. Daniel Winterhalter, Jet Propulsion Laboratory

Heliophysics Subcommittee (2012-2014):
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Co-Chair: Dr. Jeffrey Hughes, Boston University
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Dr. Leonard Strachan, Smithsonian Astrophysical Observatory
Dr. Charles Swenson, Utah State University

NASA Headquarters
Dr. Jeffrey Newmark, NASA HQ
Jennifer Rumburg, NASA HQ

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Introduction

The Agency's Heliophysics strategic objective is to **understand the Sun and its interactions with the Earth and the solar system, including space weather.** The heliophysics National Research Council (NRC) 2013 Decadal Survey, *Solar and Space Physics: A Science for a Technological Society*, articulated the scientific challenges for this field of study and recommended a slate of design reference missions to meet them, to culminate in the achievement of a predictive capability to aid human endeavors on Earth and in space. The Heliophysics Division addresses its Agency objectives and the NRC Decadal Survey recommendations in the context of our National Space Policy by working to answer these fundamental science questions:

- What causes the Sun to vary?
- How do the geospace, planetary space environments and the heliosphere respond?
- What are the impacts on humanity?

To answer these questions, NASA's Heliophysics Division is implementing a program to achieve three overarching science goals:

- ***Solve the Fundamental Mysteries of Heliophysics*** (F), Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system
- ***Understand the Nature of our Home in Space*** (H), Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system
- ***Build the Knowledge to Forecast Space Weather Throughout the Heliosphere*** (W), Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth

NASA aligns its science programs with National Space Policy and works towards implementing the priorities defined in the Decadal Survey produced by the National Research Council of the National Academies. Decadal surveys are the result of a science and mission prioritization process executed by expert panels using broad community input gathered by representative committees. This Heliophysics Science and Technology Roadmap has been developed by the NASA Advisory Council's (NAC) Heliophysics Subcommittee, with substantial input from the Heliophysics community, to look at strategies for implementing the Decadal Survey recommendations. The Heliophysics Science and Technology Roadmap provides the framework for guiding investment choices both on tactical and strategic scales and in the context of the Decadal Survey. To achieve the science objectives of the Heliophysics Division (HPD), the roadmap recommends a strategy that leverages all program elements of the Division. The recommendations include a robust research program and new missions to be deployed within the Explorer, Solar Terrestrial Probe (STP), and Living With a Star (LWS) flight programs, establishing the queue of science targets as shown in Figure 1. The

Heliophysics research strategy is based upon prioritized, yet flexible, science objectives. The roadmap includes technology development efforts and scientific research priorities to enable future missions in the priority areas.

The Heliophysics Roadmap Team was charged with implementing the 2013 Heliophysics Decadal Survey (DS). The Decadal Survey establishes strategic objectives and initiatives, and was based on a set of reasonable budget expectations. The budget situation changed dramatically between the beginning of the Decadal Survey and the publication of the Roadmap. The difference in projections amounts to an unplanned deficit of $100M per year by 2024, which has significant ramifications for the implementation program.

The Decadal Survey provides guidance for completion of the recommendations when the Heliophysics operating budget is highly constrained, although it did not foresee the magnitude of the shortfall. In accordance with this guidance, this Roadmap prioritizes the existing program, the Research program and the Explorer program ahead of the new recommended strategic missions. The Roadmap provides implementation of the Decadal Survey's highest priorities, including the implementation of NASA's portion of the Diversify, Realize, Integrate, Venture, and Educate (DRIVE) program, augmentation of the Heliophysics Explorers, and a rebalancing of the Heliophysics Research and flight portfolio. The time frame for this implementation is delayed from 2016 to 2019. Given the current budgetary situation, the Heliophysics Roadmap recommends that Heliophysics Division (HPD) 1) remain flexible in its program implementation, 2) utilize the full range of flight opportunities (e.g., sounding rockets, CubeSats, hosted payloads, etc.) to achieve its science objectives, 3) protect the core Research program, and 4) urgently develop ways to increase its flight opportunities that are needed to meet the goals of the Decadal Survey subject to the budget shortfall that emerged since its development.

Heliophysics, The Science

Heliophysics encompasses science that improves our understanding of fundamental physical processes throughout the solar system, and enables us to understand how the Sun, as the major driver of the energy throughout the solar system, impacts our technological society. The scope of heliophysics is vast, spanning from the Sun's interior to Earth's upper atmosphere, throughout interplanetary space, to the far reaches of the heliosphere, where the solar wind interacts with the local interstellar medium. Heliophysics incorporates studies of the interconnected elements in a single system that produces dynamic space weather and that evolves in response to solar, planetary, and interstellar conditions.

All of NASA's space missions (including the inhabited ISS) and much of our nation's power grid, communications and navigation infrastructure (such as the critical Global Positioning System [GPS]) are operating in an environment driven by the highly variable output from the Sun. Solar flares that accelerate charged particles to nearly the speed of light and powerful coronal mass ejections inflate the Van Allen radiation belts, drive the aurora and powerful electric currents on Earth, violently churn the ionosphere and uppermost layers of the atmosphere, and can disrupt our technologies in space and on the ground, or be harmful to astronauts. NASA's Heliophysics program provides the research and technological development necessary for the scientific understanding of how space weather affects human and robotic space exploration and the habitability of Earth and other worlds. The models and research tools NASA develops to interpret heliophysics data are expected to lead to substantial improvements in operational space weather monitoring.

Heliophysics uses our local space environment as a natural laboratory that can be directly probed with satellites. Planets and solar systems are commonplace around other nearby stars and throughout the universe. The fundamental physical processes active in our near-space environment are also at work in these distant places humans cannot visit. Increasing understanding of our home in space therefore furthers humanity's knowledge of some of the most basic working principles of the universe. As exploration extends further into space, and as society's technological infrastructure is increasingly dependent on assets that are impacted by the space environment, a broader and fundamental understanding of these governing processes becomes ever more important and relevant.

The Decadal Survey identifies four science objectives:

- Determine the origins of the Sun's activity and predict the variations of the space environment.
- Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.
- Determine the interaction of the Sun with the solar system and the interstellar medium.
- Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

This Heliophysics Roadmap follows the science organizing structure of the 2009 Roadmap, and includes updated Research Focus Areas (RFAs) to align with the science objectives identified by the Decadal Survey.

Guiding Principles

This Roadmap's charter was to implement the recommendations of the Decadal Survey within the revised fiscal constraints provided by NASA Headquarters. This Roadmap neither reprioritizes nor alters the Decadal Survey recommendations and science objectives. A main theme within the Decadal Survey is the assertion that the current Heliophysics program is unbalanced, with comparatively too few resources devoted to competed research programs and the PI-led Heliophysics Explorer program (including Missions of Opportunity, MO). The Decadal Survey recommends that the Heliophysics portfolio rebalance from its current status, 2/3 budget allocation for major flight projects plus 1/3 budget allocation for Research and Explorers, to a ~50/50 split. This rebalancing recognizes the enormous contribution of the PI-led Explorer program to scientific advancement and discovery and the underfunding of the Research program during the past few years.

To achieve this rebalancing, the Decadal Survey committee was clear in its prioritization:

- Complete the current flight program,
- Implement a new DRIVE initiative,
- Accelerate and expand the Heliophysics Explorer/MO program.

The Decadal Survey also recommends new science targets for the Solar Terrestrial Probes (STP) and Living With a Star (LWS) strategic flight programs, but emphasizes that implementing these missions should not interfere with the three core priorities listed above.

In addition to specific recommendations for program implementation, the Decadal Survey outlined the following 'guiding principles,' which are endorsed here:

- To make transformational scientific progress, the Sun, Earth, and heliosphere must be studied as a coupled system;
- To understand the coupled system requires that each sub-discipline be able to make measurable advances in achieving its key scientific goals; and
- Success across the entire field requires that the various elements of the Heliophysics research program— the enabling foundation comprising theory, modeling, data analysis, innovation, and education, as well as ground-based facilities and small-, medium-, and large-class space missions—be deployed with careful attention to both the mix of assets and to the schedule (cadence) that optimizes their utility over time.

These guiding principles form a vision for Heliophysics, in which the primary sub-disciplines make scientific progress through a balanced portfolio of flight projects – from sounding rockets to CubeSats to large missions – theoretical and observational investigations, while recognizing that these pieces are embedded within a larger system science framework. Achieving this vision requires a rebalancing of the Heliophysics program.

Rebalancing the Program

Since the release of the Decadal Survey, the Heliophysics budget was reduced and out-year growth sharply curtailed. Figure 1 shows the Heliophysics Roadmap implementation profile side-by-side with the Decadal Survey recommended profile. Note that by the end of the decade, the difference between the assumed Decadal Survey budget and the Roadmap budget is \$100M/year, a 15% reduction. For comparison, the entire competed research program is currently \$63M/year, a Small Explorer (SMEX) mission is cost-capped at ~\$180M (total Life Cycle Cost (LCC)), and the recommended PI-led STP missions are cost-capped at \$520M LCC per mission. After 2024 inflation of 1% is applied. The lack of inflation adjustment over the next decade faced by the Heliophysics program represents a yearly cut to the budget in real-year dollars, and comes on top of additional budget cuts, such as those imposed by Sequestration in 2013. In short, the constrained budget and lack of future inflation-adjusted growth are major threats to the ability of Heliophysics to achieve a robust Research program and diverse flight programs in the spirit of the Decadal Survey's 'guiding principles'.

The Decadal Survey noted that their budget assumptions precluded the recommended rebalancing of the Heliophysics portfolio until after 2017. The Heliophysics Roadmap budget projections for 2015 through 2019, are based on the President's FY15 budget request and were produced after the release of the Decadal Survey. They therefore inherently exclude any of the recommended rebalancing in this time frame.

Implementing the current program, which is the highest priority of the Decadal Survey, makes it impossible for this Roadmap to implement the remaining recommendations until after the launch of Solar Probe Plus (SPP), currently scheduled for a launch readiness in 2018. The Heliophysics Roadmap implementation strategy shown in Figure 1 follows the recommended priorities of the Decadal Survey in the context of a reduced 2015 budget along with reduced out-year 2015-2019 projections.

After the launch of SPP, a funding wedge opens up, and the HPD can fully implement the DRIVE initiative, and can immediately expand the Explorer program. Because of their importance for ensuring a vibrant Heliophysics Research program, both the competed research and Explorer program wedges grow within the planned budget, so that the real-year dollar amounts devoted to each program are commensurate with the recommendations of the Decadal Survey. However, the planned budget makes it impossible to implement the cadence of STP and LWS programs proposed by the Decadal Survey. Future roadmaps and the Decadal Survey Midterm Assessment must re-examine the implementation of the DS science targets to determine if science objectives could be achieved through more cost effective means. In addition, these committees may need to adjust the science objectives of the STP missions to protect the DRIVE and Explorer program augmentation priorities in the Decadal Survey.

The DS highlighted the importance of understanding and monitoring space weather and its effects on our technological society. The LWS program as it currently exists, both through targeted research opportunities, the LWS flight missions, and use of HSO assets, contributes to our understanding of the physical drivers of space weather and enables predictive capabilities. The LWS program does not, however, have the resources to maintain essential components of a robust space weather program. To overcome this obstacle, the DS recommended the initiation of a new program with a funding of $100-200 M/year to advance space weather and climatology observations, but only if it did not impinge on the development and timely execution of the recommended research program. Without an influx of new funding beyond what is required to maintain healthy Heliophysics Research and flight programs, this recommendation of the DS cannot be implemented as written and is not addressed in this Roadmap. Strategic use of the DRIVE augmentation and continued healthy funding of the LWS program may provide solutions to achieving some of these goals, but a robust space weather and space climatology program as envisioned by the DS is outside the scope of the current Heliophysics budget.

The Heliophysics Roadmap recommends implementation of an affordable and effective Research program that addresses the highest scientific priorities with the overall aim of understanding the coupled Sun-Earth-heliosphere system, urgently requiring that HPD focus on lower-cost options for its flight programs. Identifying and prioritizing domestic and international partnership missions and shared-launch opportunities is paramount. Additionally, Explorers and MOs are capable of groundbreaking science, so HPD will also prioritize developing an environment in which low-cost small spacecraft (well below the current Small Explorer budget) can be flown once every 12-18 months, with the goal of addressing the science of the coupled Sun-Earth system as outlined in the DS by 2024. A robust instrument development program could yield advances in miniaturization and capabilities enabling equivalent science exploration on smaller, less costly platforms.

However, some science objectives can only be met with the larger strategic missions. Even with an enhanced Explorer program and Low Cost Access to Space (LCAS) projects, certain critical science objectives will be unfulfilled given the constraints of the current budget outlook. Full completion of the Decadal Survey's recommended science queue is impossible within the decade.

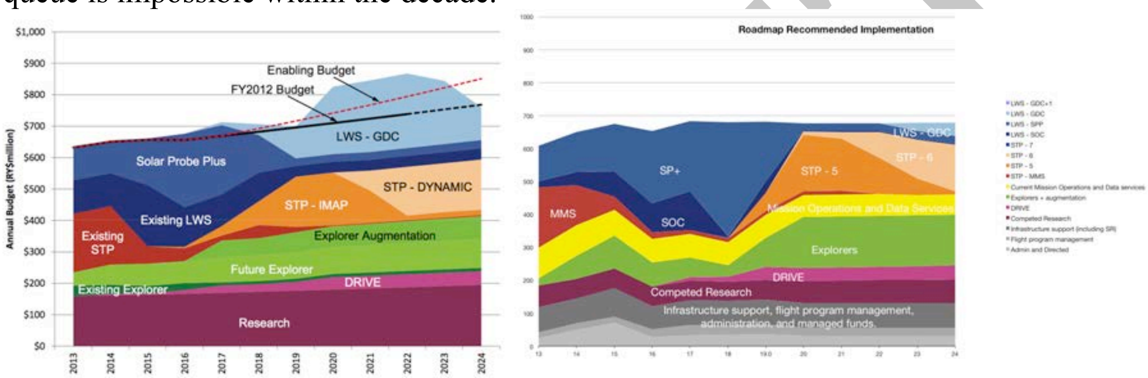


Figure 1. The Decadal Survey budget, left, and Roadmap budget, right. At the end of the decade there is a $100M/year difference in the budgets. The Roadmap has included more detail in the "Research" line, showing that the competed elements are only a portion of that bar and that the DRIVE initiative adds about 50% to the competed programs by the end of the decade. Note the temporary increase in funding for FY14 and FY15 is due to an ~$33M and ~$55M respective increase in funds managed by HPD for SMD. These funds are not available for use by Heliophysics.

Heliophysics System Observatory (HSO)

As highlighted by the Decadal Survey, Heliophysics Research has increasingly focused on interconnected pathways of the different heliophysics regions of study. The fleet of solar and space physics observatories – the Heliophysics System Observatory (HSO) – enables studies of the globally connected Sun-Earth-heliosphere system. HSO provides the system level view of the connected science recognized as a key to making future advancements. With decreased launch frequency of Explorer and strategic missions envisioned in this Heliophysics Roadmap, maintaining observations of key regions will become increasingly difficult.

Each Heliophysics mission, in formulation or in operation, has been selected with well-defined, specific, and focused science objectives. The data from these singular missions combine to create a comprehensive suite of coupled measurements that are used to study the dynamics and interconnectivity of the system as a whole. With each newly selected mission, this distributed network – the Heliophysics System Observatory, is enhanced and the community has developed the means to combine these singular science investigations. The combination of these observations and robust state-of-the-art models are quickly advancing our scientific understanding. Finally, the development of the research tools for interpretation of the data and the models are leading to substantial improvements in the research to operations aspects of space weather.

Science Targets

The Decadal Survey (DS) identified four high-priority science targets requiring the larger resources afforded by the STP and LWS strategic mission lines. These science targets will address the most urgent and compelling science issues in heliophysics and provide opportunities of discovery as these targets explore fundamental processes in novel ways. The science targets and DS Design Reference Missions are discussed in detail in Chapter 5.

High-Priority Science Targets:

STP - Heliospheric Boundary and Solar Wind Plasma: To understand the outer heliosphere and its interaction with the interstellar medium and to understand the physics of particle acceleration throughout the heliosphere. This is illustrated by the DS reference mission Interstellar Mapping and Acceleration Probe – IMAP.

STP - Lower Atmosphere Driving: To provide a comprehensive understanding of the variability in space weather driven by lower-atmosphere weather on Earth. This is illustrated by the DS reference mission Dynamical Neutral Atmosphere-Ionosphere Coupling –DYNAMIC.

STP – Magnetosphere-Ionosphere-thermosphere Coupling: To determine how the magnetosphere-ionosphere-thermosphere system is coupled and how it responds to solar and magnetospheric forcing. This is illustrated by the DS reference mission Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation – MEDICI.

LWS - Geospace Dynamics Coupling: To study in an integrated fashion how the ionosphere-thermosphere-mesosphere system responds to dynamical forcing. This is illustrated by the DS reference mission Geospace Dynamics Constellation – GDC.

For budgetary planning purposes, the Decadal Survey produced design reference missions, with notional payloads and investigative strategies. However, for PI-led missions, the specific implementation architecture for each mission should be competed. Furthermore, prior to competition, the notional mission science objectives defined by HPD should take into account recent science advancement and discoveries by other missions and research programs. In some cases, a re-scope of those science objectives may be necessary.

This Heliophysics Roadmap also includes a science traceability matrix, which identifies those science areas that are inadequately addressed by current or planned missions. These "science targets" flow directly from the Heliophysics Decadal Survey. In some cases these science targets are appropriate for strategic missions that do not fit within the current cost caps of either the LWS or STP flight programs. Closure on these targets will require technological advancements to reduce cost, complexity, and risk associated with these larger mission concepts. In other cases, the science objectives are appropriate for the Explorer program.

Missions in Formulation/Development
This Heliophysics Roadmap strongly endorses the following missions in development that address key program objectives:

Magnetospheric Multiscale (MMS) will solve the mystery of how magnetic fields around Earth connect and disconnect, explosively releasing energy via a process known as magnetic reconnection. MMS consists of four identical spacecraft that will provide the first three-dimensional views of this fundamental process that occurs throughout our universe. MMS uses Earth's protective magnetic space environment, the magnetosphere, as a natural laboratory to directly observe how it interacts with the sun's extended magnetic field, which can result in reconnection.

Solar Probe Plus (SPP) will be the first mission to visit a star. It will fly the closest any spacecraft has ever come to the Sun and will travel into one of the last unexplored regions of our solar system, the Sun's corona. By directly probing the solar corona, this mission will revolutionize our knowledge and understanding of solar wind heating and of the origin and acceleration of the solar wind, critical questions in heliophysics that have been ranked as top priorities for decades.

The Solar Orbiter Collaboration (SOC) is a collaborative mission with the European Space Agency (ESA) that will provide close-up views of the Sun's polar regions, which are poorly observed from Earth. The goals of this mission are to determine in situ the properties and dynamics of plasma, fields, and particles in the near-Sun heliosphere; to survey the fine detail of the Sun's magnetized atmosphere; to identify the links between activity on the Sun's surface and the resulting evolution within the corona and inner heliosphere; and to characterize the Sun's polar regions and equatorial corona from high latitudes.

The **Ionospheric Connection Explorer (ICON)** will probe the extreme variability of Earth's ionosphere with in situ and remote-sensing instruments. ICON seeks to understand fluctuations in the ionosphere that interfere with signals from communications and global positioning satellites, causing reduced or denial of service, and subsequently can have an economic impact on the nation.

Global-scale Observations of Limb and Disk (GOLD) is an imaging instrument that will fly on a commercial communications satellite in geostationary orbit to image the Earth's thermosphere and ionosphere to examine the response of the Earth’s upper atmosphere to forcing from the Sun and the lower atmosphere.

Chapter 1. Heliophysics: The Science

The four science disciplines of the Science Mission Directorate—Earth Science, Heliophysics, Planetary Science, and Astrophysics—together embody NASA's commitment to improving our knowledge of the Sun, the Earth and the other planets of our solar system, and the universe beyond. The specific agency-level Strategic Objective (1.4) as defined in the 2014 NASA Strategic Plan for the Heliophysics Division (HPD) is to "understand the Sun and its interactions with Earth and the solar system, including space weather." The formulation of a strategy for Heliophysics research begins with a clear exposition of the scientific goals that flow down from this directive. The 2013 NRC Decadal Survey, "Solar and Space Physics: A Science for a Technological Society," identifies four broad science goals and twelve science challenges for heliophysics. These twelve science challenges constitute a list of Heliophysics mission objectives for the coming decade. The Traceability Matrix in Appendix E summarizes the mapping of these science challenges to current and planned missions. It also identifies gaps in our science coverage. The Heliophysics System Observatory Key Systems Science Measurements graph in Appendix D, emphasizes the importance of the continuity of observations.

We identify three broad and interconnected top-level objectives formulated in support of the scientific and exploration aims of NASA:

Solve the Fundamental Mysteries of Heliophysics (F).
Understand the Nature of our Home in Space (H).
Build the Knowledge to Forecast Space Weather Throughout the Heliosphere (W).

These three roadmap objectives encompass a set of 13 research focus areas (RFAs) that define the frontiers of knowledge in heliophysics. Each of these RFAs is examined thoroughly in the remainder of this chapter. For each RFA, the associated Decadal strategy science goals and science challenges are also identified. The RFAs and the 12 Decadal science challenges are used to identify gaps in our science program leading to the recommended prioritized science targets from the Decadal Survey. The targets are the mission objectives for future Solar Terrestrial Probes (STPs) and Living With a Star (LWS) strategic mission lines, as well as candidate objectives for future Explorer missions and potential partnership missions. The science traceability matrix in Appendix E identifies the complex interrelationships between each of these prioritized science targets and illuminates how each science target fits into the hierarchy of goals required to accomplish future Heliophysics missions.

One of our objectives, "Solve the Fundamental Mysteries of Heliophysics", focuses on understanding fundamental physical processes. Addressing these problems will have a direct benefit to the goals and research focus areas of the Astrophysics, Earth Science, and Planetary Science Divisions of the Science Mission Directorate, see the introduction to Research Focus Area F for more details.

Solve the Fundamental Mysteries of Heliophysics (F)

Explore the physical processes in the space environment from the Sun to the Earth and *throughout the Solar System.*

The Sun, our solar system, and the universe consist primarily of plasma. Plasmas are more complex than liquids and gases because the motions of electrons and ions produce both electric and magnetic fields. The electric fields accelerate particles, sometimes to very high energies, and the magnetic fields guide their motions. This results in a rich set of interacting physical processes, including intricate exchanges with the neutral gas in planetary atmospheres.

Although physicists know the laws governing the interaction of electrically charged particles, the collective behavior of the plasma state leads to complex and often surprising physical phenomena. As the foundation for our long-term Research program, we will work towards a comprehensive scientific understanding of the fundamental physical processes that control our space environment.

The processes of interest occur in many locations throughout the universe, although with vastly different magnitudes of energy, size, and time. By quantitatively examining similar phenomena occurring in different regimes with a variety of techniques, we can identify the important controlling mechanisms and rigorously test our developing knowledge. Both remote sensing and in situ observations will be utilized to provide the complementary three-dimensional, large-scale perspective and the detailed small-scale microphysics view necessary to see the complete picture.

We identify five research focus areas, which are described in more detail in the sections that follow, which will solve the fundamental mysteries of Heliophysics: magnetic reconnection (F1), particle acceleration and transport (F2), ion-neutral interactions (F3), creation and variability of magnetic dynamos (F4), and waves and turbulence (F5). These interdisciplinary topics also benefit the research programs of the Astrophysics, Earth Science, and Planetary Science Divisions of the Science Mission Directorate.

Plasmas and their embedded magnetic fields affect the formation, evolution, and destiny of planets and planetary systems. Our habitable planet is shielded by its magnetic field, protecting it from solar and cosmic particle radiation and from erosion of the atmosphere by the solar wind. Planets without a shielding magnetic field, such as Mars and Venus, are exposed to those processes and evolve differently. On Earth, the magnetic field changes strength and configuration during its occasional polarity reversals, altering the shielding of the planet from external radiation sources. How important is a magnetosphere to the development and survivability of life?

Planetary systems form in disks of gas and dust around young stars. The conditions within the stellar astrosphere, including stellar UV emission, stellar winds, and energetic particles, influence the formation of planets by affecting both the internal structure of the disk and its interaction with the parent star. The role of magnetic fields in this formation process has not been fully integrated with other parts of the process. The study of similar regions in our solar system, such as dusty plasmas surrounding

Saturn and Jupiter, will help explain the role of plasma processes in determining the types of planets that can form and how they later evolve. The mission to understand the conditions necessary to support life and the search for Earth-like exoplanets will benefit from a refined understanding of planetary formation and evolution informed by a detailed investigation of heliospheric plasma processes.

Magnetic reconnection facilitates the conversion of magnetic energy to kinetic and thermal energy and likely plays a key role in the heating of stellar and accretion disk coronae. Shocks are widely observed in astrophysical systems in the form of supernova shocks, which are a predicted source of galactic cosmic rays, at the termination of astrophysical jets, and more generally during collisions and mergers of galaxies. Turbulence facilitates accretion onto compact astrophysical objects, mediates the conversion of the kinetic energy of large-scale turbulent motions to plasma heat via a turbulent cascade, and influences the mechanisms of star and planet formation. Pulsars are rapidly rotating magnetic stars that can be exploited as invaluable probes of physics in extreme astrophysical environments, and many rotating magnetized systems are observed to launch astrophysical jets. Studies of these universal mechanisms within the heliosphere, in which it is often possible to make detailed in situ measurements of all aspects of the electromagnetic fields and particle velocity distributions, can contribute to significant leaps in our understanding of the fundamental plasma physics phenomena that impact this broad range of astrophysical systems.

Understand magnetic reconnection (F1)

Magnetic reconnection is a topological change in the magnetic field configuration that releases stored magnetic energy into the plasma confined to orbit about the field. Reconnection is responsible for the energy release in solar flares, and is intimately associated with the efficient acceleration of energetic electrons and ions during the impulsive phase of flares. In the solar corona, reconnection can sever large plumes of dense plasma from the magnetic fields that anchor them close to the Sun, allowing them to expand into the solar system. Reconnection at the outer boundary of the planetary magnetospheres and within magnetotail regions is responsible for the coupling between the solar wind and the magnetosphere that drives aurorae and geomagnetic storms. The consequences of reconnection can be damaging to communication systems and electrical

F1

Addresses Goal 1 (Determine the origins of the Sun's activity and predict the variations in the space environment)

Addresses Goal 2 (Determine the dynamics and coupling of the Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs)

Addresses Goal 4 (Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe)

Addresses Challenge SH-3 (Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate throughout the heliosphere)

Addresses Challenge SWMI-1 (Establish how magnetic reconnection is triggered and how it evolves to drive mass, momentum, infrastructure on Earth and to assets in space, as well as to the presence of humans in space.

Reconnection is fundamentally a multiscale process. The large-scale configuration of the magnetic field creates the conditions under which reconnection can occur, but the explosive conversion of magnetic to kinetic energy originates in a region called the diffusion region, which is very small in comparison. For example, reconnection at the Earth's magnetopause (the boundary separating the solar wind and terrestrial magnetic fields) occurs in the diffusion region with a cumulative area on the order of hundreds of square kilometers, compared to a total magnetopause surface area of approximately 60 billion square kilometers. Current solar imaging techniques are insufficient to resolve the diffusion region associated with solar flares and coronal mass ejections (CMEs). While there have been a few encounters with the diffusion region in the near-Earth space environment, the systematic study of this phenomenon is just beginning. The near-Earth environment is the best available natural laboratory to study this type of magnetic reconnection. The reconnection process in space is inherently different from that within the laboratory setting because the plasmas are collisionless; all interactions are mediated via electromagnetic forces and wave activity. The physical processes that initiate and control collisionless reconnection remain to be measured.

Much of our basic theoretical understanding of reconnection comes from a magnetohydrodynamics (MHD) perspective. Although this approach has provided important insight, it is inherently limited in that it cannot address the very small scales at which ions and electrons decouple from the magnetic field or the detailed particle energization process. Important questions remain unanswered both observationally and theoretically: What initiates the reconnection process? What are the kinetic processes that occur and what is their role? What is the range of scale sizes of the region over which reconnection occurs in different regimes? What determines if reconnection is quasi-steady or bursty? What mechanisms or boundary conditions control the spatial and temporal scales? What is the three-dimensional structure of the reconnection region and how does this structure affect particle acceleration?

F2

Addresses Goal 2 (Determine the dynamics and coupling of the Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs)

Addresses Goal 3 (Determine the interaction of the Sun with the solar system and the interstellar medium)

Addresses Goal 4 (Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe)

Addresses Challenge SH-3 (Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate throughout the heliosphere)

Addresses Challenge SH-4 (Discover how the Sun interacts with the local interstellar medium)

Addresses Challenge SWMI-2 (Identify the mechanisms that control the production, loss, and energization of energetic particles in the magnetosphere)

Understand the plasma processes that accelerate and transport particles (F2)

High-energy particles accelerated at the Sun and within interplanetary space as well as galactic cosmic rays (GCRs) from outside the solar system pose a serious hazard to human and robotic exploration. Energetic particles produced or trapped within planetary magnetospheres can damage important technological assets in those locations. Predicting these effects requires a fundamental understanding of where and how particles in space can be accelerated and how they are transported.

More than one mechanism can operate to produce a given energetic particle population at a given location. Moreover, energetic particles are accelerated both at localized sites (solar flares, planetary bow shocks, magnetotail reconnection sites, auroral acceleration regions, and radiation belts), and globally (coronal and interplanetary shocks, corotating interaction regions and global merged interaction regions in the solar wind, and the termination shock in the heliosheath). Important processes for near-term investigation include quasi-static electric fields parallel to the background magnetic field, wave electric fields, stochastic (Fermi) acceleration, and the drift of particles along a component of the electric field such as that occurring in shocks and the magnetotail.

Specific examples of phenomena that, upon investigation, should yield a deeper understanding of plasma processes that accelerate and transport particles are the aurora, CMEs, and the solar wind termination shock. The Earth's aurora provides a unique opportunity to understand acceleration by parallel electric fields and waves. Particle acceleration at CME shock fronts is a leading candidate for the production of gradual solar energetic particle (SEP) eves. New observations at the solar wind termination shock suggest that suprathermal ion populations dominate the kinetic energy of the plasma in the heliosheath, which challenges our views on how particle energization occurs in the outer heliosphere.

An understanding of the heating and acceleration of thermal plasmas is also vital as these form seed populations for subsequent energization or mediate the transport and acceleration of energetic particles. In terrestrial and planetary magnetospheres, for example, thermal plasmas can be accelerated to sufficiently high energies to form ring currents and radiation belts. The solar wind transports energetic particles and provides acceleration regions through its interaction with magnetospheres, the termination shock, stream interaction regions, and interplanetary CMEs. The origin and acceleration of the solar wind is also not well understood, representing a large gap in our knowledge of fundamental processes.

Understand ion-neutral interactions (F3)

There are many locations throughout the solar system where interactions between charged and neutral particles strongly affect the behavior of the system. Charged and neutral species respond to different forces but interact through collisions. These collisions result in chemical reactions, charge exchange, and transfer of energy and momentum between the populations. Most important for near-term study is to understand the large-scale balance between gravitationally and magnetically controlled components of the system.

Planetary atmospheres, including that of the Earth, are affected directly by ultraviolet (UV) and infrared radiation from the Sun. Charged particles are produced when this radiation is absorbed and energy from this process is redistributed in a variety of ways before being reradiated to space. The charged particles may also be influenced by a magnetic field. The Sun's interplanetary magnetic field produces a stress known as mass loading. The presence of a planetary magnetosphere provides additional pathways for redistributing the energy from the Sun and suppresses a direct interaction of the neutral atmosphere with the charged particles of the solar wind.

At Earth, the upper atmosphere is also subject to energy and momentum inputs from below, carried by waves excited in the lower atmosphere by a variety of processes, including absorption of longer wavelength solar radiation, wind blowing over mountains, and latent heat release in deep tropical clouds. Variations associated with these upward propagating inputs modulate the large-scale temperature, winds, and composition in the middle and upper atmosphere. Such processes also operate in the atmospheres of Venus and Mars.

When charged and neutral particles exist in the presence of a magnetic field, the mobility of the magnetized plasma becomes anisotropic and drag

F3

Addresses Goal 2 (Determine the dynamics and coupling of the Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs)

Addresses Goal 3 (Determine the interaction of the Sun with the solar system and the interstellar medium)

Addresses Goal 4 (Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe)

Addresses Challenge SH-2 (Determine how the Sun's magnetism creates its hot, dynamic atmosphere)

Addresses Challenge SH-4 (Discover how the Sun interacts with the local interstellar medium)

Addresses Challenge SWMI-3 (Determine how the coupling and feedback between the magnetosphere, ionosphere and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind)

Addresses Challenge AIMI-1 (Understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over global, regional and local scales)

Addresses Challenge AIMI-2 (Understand the plasma-neutral coupling processes that give rise to local, regional, and global-scale structures and dynamics in the AIM system) forces between the plasma and the neutral gas introduce complex electrodynamic interactions. Electric fields are generated as the neutral winds or upward propagating atmospheric waves drag ions across magnetic field lines in a variety of neutral wind dynamos. These dynamo electric fields map along magnetic field lines to drive plasma motions in regions outside of the dynamo. Such dynamo interactions dramatically increase the complexity of the atmosphere's response to forcing, modifying the global distribution of the plasma and creating instabilities that lead to density structures spanning a wide range of scales. In turn, ionospheric motions can also alter neutral winds. Plasma moving in response to electric fields of solar wind origin can accelerate or decelerate the neutral atmospheric gas through drag forces and change its circulation patterns. Small-scale plasma structures that result from these interactions influence the propagation of radio waves and affect communications and navigation systems.

The solar chromosphere, a dynamic and highly structured region between the photosphere and corona, plays a crucial, but poorly understood, role in supplying mass and energy to the solar corona and solar wind. The chromosphere is partially ionized, with the ionization state determined largely by time-dependent, nonlocal, and nonlinear radiation transport processes. Electromagnetic forces only affect the ions and electrons; yet their collisional coupling with neutral atoms is important for, and may dominate, the dynamics and energetics of the chromosphere. Understanding the interaction of the neutral and ionized constituents is essential for understanding the role of the chromosphere in energizing the corona and heliosphere.

The multi-species solar wind plasma gets shocked and decelerated at the heliospheric termination shock as it encounters and interacts with inflowing interstellar plasma and neutral atoms. Although these interactions play critical roles in determining the dynamics, structure, and evolution of the heliosheath and the interaction of the heliosphere with the interstellar medium, the physical processes involved are poorly understood and present significant challenges.

In all of these contexts, the interactions between charged and neutral species drive the nonlinear, seemingly separate behavior of both species. It is not possible to specify the state of the entire system from only instantaneous knowledge of a single component or from simple monitoring of external drivers. Rather, both initial states and the evolutionary time scales must be understood over a wide spectrum of spatial scales. Meeting these requirements presents our primary challenge for future progress.

Understand the creation and variability of solar and stellar magnetic dynamos (F4)

The generation of cosmic magnetic fields is a universal process that occurs wherever highly conducting fluids and plasmas are driven into motion by large-scale forces. Magnetic dynamos operate in our Sun, other stars, accretion disks, active galactic nuclei, Earth (both the core and the neutral-wind atmosphere; see F3), and in other planets. The magnetic fields, which are maintained indefinitely against ohmic diffusion, are the source of a wide range of important phenomena, not only in the Sun–Earth system, but also throughout the heliosphere and the universe beyond. The solar dynamo has operated throughout the Sun's lifetime, even regulating the formation of the Sun and our planetary system. Today, the magnetic fields that it generates control and influence many events that affect the technological functions of our society. The Sun's magnetic field carves out a protective bubble in the local interstellar medium and decreases the flux of damaging galactic cosmic rays that enter the solar system. The magnetic dynamo is thus a factor in the habitability of planets. The magnetic field generated at the Sun is stressed by motions of the plasma in which it resides until enormous amounts of stored energy are released explosively as electromagnetic radiation, energetic particles, mass ejections, and magnetic fields. This energy reaches the Earth over time scales that range from eight minutes to several days, causing dramatic space weather disturbances to our environment.

F4

Addresses Goal 1 (Determine the origins of the Sun's activity and predict the variations in the space environment)

Addresses Goal 2 (Determine the dynamics and coupling of the Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs)

Addresses Goal 4 (Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe)

Addresses Challenge SH-1 (Understand how the Sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere)

The most visible indicator of the solar dynamo is the well-known "11 year" sunspot cycle, which in fact varies from 9 to 14 years in its duration and by a factor of 5 in its amplitude. The polarity switches every cycle, so that the overall period is nominally 22 years. The factors that control the variability from cycle to cycle still elude us. For example, why the solar dipole and heliospheric magnetic field in the recent solar minimum were only half of their usual values at the minima of the previous cycles is an urgent puzzle. The response at Earth was immediate and dramatic. The Earth's radiation belts nearly disappeared, galactic cosmic rays reached an all time high in the space age, and the upper atmosphere became exceptionally cold and tenuous, demonstrating that the solar dynamo is a key factor in the prediction of long-term space weather and atmospheric change.

Helioseismic data from ground and space-based observations provides some support to the flux transport dynamo, in which the toroidal fields are amplified deep in the convection zone and the poloidal fields are amplified by poleward migration of erupted flux, however vigorous exploration of alternatives continues. These observations have also led to the discovery of two regions of strong radial shear in the internal rotation rate of the Sun, each thought to give rise to its own dynamo: one located just a few percent of the radius of the Sun below the surface and the other at 70% of the radius (very close to the base of the Sun's convective envelope). The predictive capabilities of these models are improving, as the models are refined based on both recent observations and the ingestion of historical observations dating back several centuries. Comparative stellar dynamo studies should reveal much about the long-term behavior of stars and the Sun and place valuable additional constraints on dynamo models. Developing an understanding of the dynamo process in sufficient detail to allow prediction is important for long-term planning for solar activity. It would also have obvious applications in trying to understand past and future periods of abnormal solar activity and the concomitant effects on terrestrial climate and planetary habitability.

Understand the role of turbulence and waves in the transport of mass, momentum, and energy (F5)

Turbulence and waves occur ubiquitously in magnetized plasmas throughout the heliosphere, exerting a strong influence on the transport of plasma particles, momentum, and energy in a wide variety of environments. Turbulence and waves also play important roles in affecting the structures and dynamics of neutral planetary atmospheres. From the stellar interior to the solar corona, flowing with the solar wind plasma to planetary magnetospheres and the outer boundary of the heliosphere and beyond, and within the coupled system of the Earth's atmosphere, ionosphere, and magnetosphere, turbulence plays a significant role in the evolution of the plasmas that fill our space environment.

Within the outer layers of the Sun, turbulent magnetoconvection is an essential element of the solar dynamo responsible for the magnetic polarity reversals on the 11-year solar cycle and the generation of the magnetic field that pervades the heliosphere and shields our home in space from the high energy cosmic radiation permeating the local interstellar environment. Waves and turbulent motion are thought to be the dominant mechanism of transport for energy from the solar interior to the solar corona. Dissipation of these turbulent motions is believed to be responsible for the heating of the solar corona to a temperature of millions of degrees and ultimately leads to the launching and acceleration of the supersonic and super-Alfvenic solar wind, although the physical

F5

Addresses Goal 1 (Determine the origins of the Sun's activity and predict the variations in the space environment)

Addresses Goal 3 (Determine the interaction of the Sun with the solar system and the interstellar medium)

Addresses Goal 4 (Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe)

Addresses Challenge SH-2 (Determine how the Sun's magnetism creates its hot, dynamic atmosphere)

Addresses Challenge SH-4 (Discover how the Sun interacts with the local interstellar medium)

Addresses Challenge SWMI-2 (Identify the mechanisms that control the production, loss, and energization of energetic particles in the magnetosphere)

Addresses Challenge AIMI-3 (Understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves influences the ionosphere and thermosphere) mechanisms responsible remain to be conclusively determined.

As the solar wind flows radially outward through interplanetary space from the Sun, its thermodynamic evolution is nonadiabatic, suggesting in situ heating of the solar wind plasma, likely to occur as a consequence of the dissipation of turbulent motions within the bulk solar wind flow. Some theories suggest that turbulence plays a key role in the acceleration of energetic particles associated with solar flares, interplanetary shocks, and the heliospheric termination shock. The transport and distribution of solar energetic particles, anomalous cosmic rays, and galactic cosmic rays throughout the heliosphere is strongly influenced by the presence and properties of turbulence in the interplanetary plasma, the determination of which is critical to safeguard human and robotic exploration of the solar system. Beyond the limits of the Sun's influence, turbulence facilitates the accretion of material onto compact objects and impacts the processes of star formation and planet formation.

The turbulent flow of shocked solar wind plasma in the magnetosheath may alter the coupling of the flow to the magnetosphere, possibly governing the transport of plasma and energy from the streaming solar wind into the Earth's magnetosphere. Waves occurring within the magnetosphere play an important role in both the energization and loss of ring current and radiation belt particles through wave-particle interactions. Establishing a thorough understanding of this process is essential to develop a predictive capability for the near-Earth environment. Wave-particle interactions also accelerate the high-energy electrons that precipitate into the polar ionosphere and generate the glowing aurorae. In neutral planetary atmospheres, surface topography and unstable shear flows excite planetary waves and gravity waves extending from planetary to very small scales. In addition, tropospheric weather systems can launch vertically propagating waves that grow in amplitude exponentially with height into the tenuous upper atmosphere. The nonlinear evolution of these amplified waves drives a turbulent cascade that leads to mixing of chemical constituents and deposits momentum and energy in the upper atmosphere. These effects turbulence produces on the plasma conductivity within the ionosphere remain an open question.

NEXT TOP LEVEL OBJECTIVE (H):

Understand the Nature of Our Home in Space (H)
Advance our understanding of the connections that link the Sun, the Earth and planetary space environments, and the outer reaches of our solar system.

Humankind does not live in isolation but is intimately affected by the space environment through our technological needs, our plans to explore the solar system, and the ultimate fate of the Earth itself. We regularly experience how variability in the near-Earth space environment impacts the activities that underpin our society. We are living with a star.

We plan to understand better our place in the solar system by investigating the interaction of the space environment with the Earth and the effect of this interaction on humankind. We intend to characterize the space environment and develop knowledge of its impact on our planet, technology, and society. Our goal is to understand the web of linked physical processes connecting Earth with the space environment.

Even a casual scan of the solar system is sufficient to recognize that habitability, particularly for humankind, requires a rare confluence of many factors. At least some of these factors, especially the role of magnetic fields in shielding planetary atmospheres, are subjects of immense interest in heliophysics. Lessons learned in the study of planetary environments can be applied to our home on Earth, and similarly the study of our own atmosphere supports the exploration of other planets.

H1

Addresses Goal 1 (Determine the origins of the Sun's activity and predict the variations in the space environment)

Addresses Goal 3 (Determine the interaction of the Sun with the solar system and the interstellar medium)

Addresses Challenge SH-1 (Understand how the Sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere)

Addresses Challenge SH-2 (Determine how the Sun's magnetism creates its hot, dynamic atmosphere)

Addresses Challenge SH-3 (Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate throughout the heliosphere)

Addresses Challenge SWMI-3 (Determine how the coupling and feedback between the magnetosphere, ionosphere and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind)

Addresses Challenge AIMI-4 (Determine and identify the causes for long-term (multi-decadal) changes in the AIM system)

Understand the origin and dynamic evolution of solar plasmas and magnetic fields throughout the heliosphere (H1)

The climate and space environment that affect Earth are determined by the plasma, energetic particle, and electromagnetic radiation outputs from the Sun. The solar output varies on many time scales, from explosive reconnection on scales of microseconds, to convective turnover taking minutes to hours, to a solar rotation period of a month, to the 22-year solar magnetic cycle, and to century-long irregular fluctuations, such as the Maunder minimum. This high degree of variability is a consequence of the emergence of the magnetic field from below the photosphere, its transport and destruction in the solar atmosphere, and the intermittent eruption of stored energy into the heliosphere as flares and CMEs. The heliospheric magnetic field also modulates the propagation of incoming GCRs. In addition, longer-term changes that can affect Earth's climate include variations in the solar radiation spectrum and in the total solar irradiance.

The solar wind is emitted from the edges of coronal holes, and it carries embedded fluctuations of magnetic field, density, and temperature, as well as energetic particle populations. All of these properties evolve as they travel through the heliosphere. Shocks accelerate the particles and interact with the other irregularities. CMEs can interact with each other. Particles collide and redistribute energy. Turbulence transfers electromagnetic and plasma fluctuation energy from large to small scales, ultimately leading to the conversion of this energy into plasma heat. The result is an ever-changing background of electric fields, magnetic fields, and charged particle radiation bombarding the Earth and near-space environment. Understanding the three-dimensional, time-varying origin and propagation of solar disturbances is one of the greatest challenges facing us. Understanding the internal configuration of the structures in the solar wind flow is another.

Precursors can provide important information about solar and interplanetary events; however, more complete predictive models based on physical principles are necessary to enable the useful assimilation of this information. As with terrestrial weather, it is not yet clear how long in advance solar activity can be predicted. Improved and continuous observations of the solar vector magnetic field, at multiple altitudes in the solar atmosphere, along with high-resolution multispectral observations of the Sun in conjunction with physics-based models driven by these data, are all critical for improving space weather forecasts.

Understand the role of the Sun and its variability in driving change in the Earth's atmosphere, the space environment, and planetary objects (H2)

Because life depends on the atmosphere and its climate, the study of solar-driven atmospheric variations is critically important. Solar energy in the form of photons and particles drives the chemical and physical structure of Earth's atmosphere. For example, UV radiation and X-rays deposited globally throughout the mesosphere and thermosphere are responsible for formation of the ionosphere. Also, while particles primarily deposit their energy at high latitudes, the resulting ionization, dissociation, and excitation of atoms and molecules can have a global effect due to dynamical processes that transport energy. Ultimately, these processes combine to drive the temperature

H2

Addresses Goal 2 (Determine the dynamics and coupling of the Earth’s magnetosphere, ionosphere, and their response to solar and terrestrial inputs)

Addresses Goal 3 (Determine the interaction of the Sun with the solar system and the interstellar medium)

Addresses Challenge SWMI-3 (Determine how the coupling and feedback between the magnetosphere, ionosphere and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind)

Addresses Challenge AIMI-4 (Determine and identify causes for long-term (multi-decadal) changes in the AIM system)

and chemical composition of the Earth's entire atmosphere. One of the urgent, unresolved questions in heliophysics is how processes in the Earth system amplify the effects of small changes in solar energy output, leading to disproportionately large changes in atmospheric parameters.

Gradual changes in solar activity, solar wind, extreme ultraviolet (EUV) radiation, and Earth's magnetic field each play a significant role in defining the longer-term variation of the geospace environment. The geospace environment is defined as the space that surrounds the Earth and is influenced by various solar system bodies. This environment begins with the Earth's upper atmosphere, including the mesosphere and thermosphere, extends outward through the ionosphere, and continues into the magnetosphere and beyond. As an example of this variation, long-term changes measured in Earth's magnetic field produce measurable changes in the ionosphere. From the solar irradiance perspective, the latest solar minimum, from late 2007 to mid-2009, marked the lowest solar EUV fluxes (and heating rates) for the longest duration in the past four solar cycles. This low solar minimum was also accompanied by a weaker than normal interplanetary magnetic field, cosmic rays at record high levels, a high tilt angle of the solar dipole magnetic field, and low solar wind pressure. These conditions generated unprecedented evidence of lower atmospheric drivers of ionosphere and thermosphere variability.

A key example of how atmospheric modification by the Sun affects life is stratospheric ozone, which acts as a UV shield for life on Earth. The very existence of the ozone layer is a direct result of solar energy deposition. Model simulations and decades of observations indicate that changes in ozone and greenhouse gases have produced long-term changes in the wind fields of the stratosphere and mesosphere that serve as the environment through which tropospherically excited waves propagate, and into which they deposit momentum and energy upon their dissipation.

Nitric oxide created at higher altitudes by processes involving solar and auroral energy may be transported to lower altitudes where it can destroy ozone. Solar energetic particles have been linked to episodic stratospheric ozone depletions, leading to alterations in planetary wave propagation and global circulation, as discussed above. It is also possible that radiation belt particles play a role as well. GCRs are modulated by the solar cycle, but their possible influence on cloud nucleation and the resulting albedo remains controversial.

Coupling processes that spread the effects of energy deposition in altitude and latitude are not well understood. The rise in CO2 concentrations has led to the observable fact that the lower atmosphere is warming while the upper atmosphere is cooling. One result of an increase in the average temperature in the lower atmosphere is that the amount of water vapor, and the available latent heat associated with raindrop formation in tropical clouds, may increase. Possible consequences include changes in the strength of upward-propagating, lower atmosphere tides and other tropical waves that can modify longitudinal structure of the ionosphere and thermosphere. An increase in the number of severe storms is also expected, which could impact ionospheric instabilities that are seeded by tropospheric gravity waves propagating into the upper atmosphere.

A major goal for the upcoming decade is to determine how our planetary environment is changing over multi-decadal scales, and to understand how the changes are embodied in or transmitted through geospace. Addressing these issues requires high time-resolution spectral observations of solar energy, measurements of the atmospheric response, as well as theory and modeling of dynamical processes that distribute effects of solar energy.

Understand the coupling of the Earth's magnetosphere-ionosphere-atmosphere system, and its response to external and internal forcing (H3)

Earth's space environment is a complex, strongly coupled system energized by a range of inputs that originate with the Sun. One important input is the magnetized solar wind rushing past Earth at a million miles per hour. The solar wind interacts with Earth's magnetic field to shape the magnetosphere, in which magnetic energy accumulates and is intermittently released in powerful bursts. This process accelerates magnetospheric plasma into Earth's auroral regions and heats the upper atmosphere, a well known effect of the aurora. Auroral heating sets the upper atmosphere into motion and modifies its composition and chemistry. Pulsating auroral drivers excite traveling atmospheric disturbances that propagate equatorward. Embedded in the atmosphere is the ionosphere, the density of which is usually driven by solar extreme UV radiation. However, its density is strongly affected by auroral-induced changes in the atmosphere, and thus by solar wind conditions.

The electric fields that develop in the magnetosphere during solar wind-induced disturbances can also strongly modify the ionosphere, drawing high-density plasma from low to high latitudes in great plumes, further enhancing the strength of geomagnetic disturbances by adding to magnetospheric pressure through high-latitude ion outflow. This is how the solar wind energy initiates a magnetic storm, with subsequent effects in the atmosphere and ionosphere that, in turn, may modify the magnetic storm strength itself. The

H3

Addresses Goal 2 (Determine the dynamics and coupling of the Earth's magnetosphere, ionosphere, and their response to solar and terrestrial inputs)

Addresses Challenge SWMI-3 (Determine how the coupling and feedback between the magnetosphere, ionosphere and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind)

Addresses Challenge SWMI-4 (Critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations from different magnetospheric systems)

Addresses Challenge AIMI-1 (Understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over global, regional and local scales)

Addresses Challenge AIMI-4 (Determine and identify causes for long-term (multi-decadal) changes in the AIM system)

flow of energy and mass in this strongly coupled system is an intensively studied problem with broad implications for our technological society and for the basic understanding of plasma processes in planetary environments. Individual parts of the system have been the target of many focused studies, yielding improved understanding of processes occurring on a wide range of temporal and spatial scales.

Equally important is to understand how these processes couple across the broad range of spatial and temporal scales in our geospace system. Atmospheric gravity waves have often been cited as the source for small-scale plasma variability. New pathways for energy coupling have recently been discovered in geospace. Recent research indicates that the response of the atmosphere to auroral forcing depends on the total energy input and the width of the auroral curtains. Daily tropospheric precipitation in equatorial rainforests releases such a prodigious amount of heat that the tides of atmospheric energy propagating upward from these storms dramatically change the upper atmosphere and ionosphere. Recent measurements have shown that meteorological disturbances like stratospheric warmings significantly alter the state of the ionosphere-thermosphere (IT) system.

It is known that the primary mechanism through which energy and momentum are transferred from the lower atmosphere to the upper atmosphere and ionosphere is through the generation and propagation of waves. The propagation of tides into the thermosphere is modulated by planetary waves within the neutral atmosphere. In turn, tides and planetary waves have been shown to modulate the transmission of gravity waves through the middle atmosphere and into the IT. The resulting IT wind perturbations can redistribute ionospheric plasma, either through the electric fields generated via the dynamo mechanism, or directly by moving plasma along magnetic field lines. The associated thermospheric density perturbations can affect satellite orbits.

The relevant coupling processes operating within the neutral atmosphere, and between the neutral atmosphere and ionosphere, involve a host of multi-scale dynamics that is not understood at present. However, there are currently no coordinated observations of neutral waves and ionospheric perturbations with sufficient space-time resolution and vertical coverage to investigate the neutral-plasma interactions associated with troposphere-ionosphere, stratosphere-ionosphere, and mesosphere-ionosphere coupling.

Understand the nature of the heliospheric boundary region, and the interactions between the solar wind and the local interstellar medium (H4).

During the last decade, the passage of the two Voyager spacecraft through the termination shock and into the heliosheath opened up the new avenue of in situ investigation of the outer regions of the heliosphere and its interaction with the local interstellar medium

H4

Addresses Goal 3 (Determine the interaction of the Sun with the solar system and the interstellar medium)

Addresses Challenge SH-4 (Discover how the Sun interacts with the local interstellar medium)

(LISM). Simultaneously, the innovative use of energetic neutral atom (ENA) measurements has enabled remote mapping of the global structure of the outer boundary of the Sun's influence and how it interacts with the interstellar medium. Such exploration of the heliospheric boundary permits advances in our understanding of how the heliospheric magnetic field protects the planets from the galactic environment, enables the characterization of the physical mechanisms arising in the interaction with the LISM, such as the process responsible for the acceleration of anomalous cosmic rays, and ultimately allows a complete understanding of our solar system's place in the galaxy and the Universe.

The outflowing supersonic and super-Alfvenic flow of the solar wind and its embedded magnetic field shields the solar system from galactic cosmic radiation. The interaction of the solar wind with the LISM depends on the ram pressure of the solar wind and the properties of the LISM (density, pressure, magnetic field, and bulk flow). These properties, particularly those of the LISM, change over the course of time, and can change dramatically on long time scales (1,000 years and longer) as the solar system encounters interstellar clouds. How do these long-term changes affect the sustainability of life in our solar system? In addition, observations from the Interstellar Boundary Explorer (IBEX) mission reveal an unanticipated feature, the "ribbon," superimposed on globally distributed ENAs originating from the heliospheric boundary. Investigating the evolution of the ribbon and the globally distributed ENAs in time, as measured at different particle energies, will invaluably aid in identifying the physical processes responsible for this intriguing feature, and shed light on the nature of the interaction between the heliosphere and the LISM.

The Voyager 2 spacecraft is currently sampling the heliosheath plasma. Unlike the region inside the termination shock, the heliosheath flow is not dominated by supersonic solar wind, but may be dominantly influenced by compressive magnetic structures, turbulence, or magnetic reconnection. The two Voyagers' passage through the termination shock were not accompanied by the anticipated peak in the anomalous cosmic ray density, providing valuable constraints on the location and possible mechanisms for their origin. The in situ measurements of the heliosheath conditions continue to yield unexpected surprises, and it is clear that much remains to be learned about this new frontier in space. In 2012, the Voyager 1 spacecraft passed through the heliopause, becoming the first human-made object to leave the heliosphere and communicate its findings back to Earth. This historic milestone enabled the first direct measurements of the conditions of the LISM, providing an invaluable probe of our neighborhood in the Galaxy.

PAGE BREAK

NEXT TOP LEVEL OBJECTIVE: W

Build the Knowledge to Forecast Space Weather Throughout the Heliosphere (W)
Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.

NASA's robotic spacecraft continue to explore the Earth's neighborhood and other targets in the heliosphere. Humans are expected one day to venture onto the surface of the Moon again and onto the surface of Mars. Both human and robotic exploration brings challenges and hazards. We plan to help safeguard these space journeys by supporting the development of predictive and forecasting strategies for space environmental hazards.

This work will aid in the optimization of habitats, spacecraft, and instrumentation, and for planning mission operation scenarios, ultimately increasing mission productivity. We will analyze the complex influence of the Sun and the space environment, from origin to destination, on critical conditions at and in the vicinity of human and robotic spacecraft. Collaborations between heliophysicists and those preparing for human and robotic exploration will be fostered through interdisciplinary research programs and the common use of NASA research assets in space.

Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers (W1)

The Sun is a variable star. Beginning with the invention of the telescope more than 400 years ago, it has been found that the Sun shows quasi-periodic behavior in sunspot occurrence, and that the Earth is susceptible to solar variability. The solar activity cycle, linked to sunspots, is approximately 11 years long. Historical records show that not all solar cycles are the same, and that there are indications that the current solar cycle may be very different from those since the dawn of the space age. The variations we have seen within these last 50 years do not reflect the full extent of solar variability and extremes. Archival records of events in ice cores and specific modeling of the infamous 1859 Carrington event indicate that more severe space

W1

Addresses Goal 1 (Determine the origins of the Sun's activity and predict the variations in the space environment)

Addresses Challenge SH-1 (Understand how the Sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere)

Addresses Challenge SH-3 (Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate throughout the heliosphere)

Addresses Challenge SWMI-3 (Determine how the coupling and feedback between the magnetosphere, ionosphere and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind)

Addresses Challenge AIMI-4 (Determine and identify causes for long-term (multi-decadal) changes in the AIM system)

weather has frequently occurred on a millennial timescale. It is important to collect long-term records of space weather events and space climate. Even the previous and benign solar cycle minimum is unusual compared to all cycles spacecraft have encountered so far; it lasted longer, and at the same time, the solar polar magnetic field was significantly weaker than in the three previous solar minimum periods. As a result, the Earth's ionosphere has reached its coldest state ever recorded, and the solar wind output of the Sun, which has waned over the course of the past decade seemingly independent of solar activity, has reached an historic low. Recognizing the importance of space measurements, the HPD has put in place new rules that will ensure preservation and open access of the data collected by past and currently operating spacecraft. Thus, future research into the extremes of the space environment can utilize effectively what this generation of robotic explorers has gathered and can fit this information into the overall context of solar and space environment variability.

The significance of characterizing extremes in heliophysics derives from its impact on our technological society. NASA, in particular, develops robotic explorers and plans to send humans beyond low-Earth orbit, where they are more vulnerable to space weather hazards. Primary hazards to assets and humans in space are solar energetic particles (SEPs) accelerated at or near the Sun, trapped particles in radiation belts around the Earth (see W4), and galactic cosmic rays (GCRs). SEPs represent a transient but high-intensity threat to space hardware and the safety of astronauts. GCRs can affect the performance of supercomputers at Earth, so knowledge of the occurrence rate and range of intensities is critical for system design purposes. For GCRs, which are modulated by the heliospheric large-scale magnetic field distribution, the priority is to characterize typical GCR conditions throughout the heliosphere, and as a function of time during the different phases of the solar cycle.

The extremes of solar events combined with the drive toward ever lighter and more compact space flight hardware frequently have caused problems for instrumentation, preventing the accurate characterization of the extremes. In some cases, post-event analysis allowed successful recovery of data. However, in order to prepare missions toward data reliability that feed a modeling environment in near-real time, new and robust technologies have to be developed. These developments will pave the way for exploring key mechanisms and regions through which extreme space weather events arise.

W2: Develop the capability to predict the origin, onset, and level of solar activity in order to identify potentially hazardous space weather events and all-clear intervals

Dramatic and rapid changes in space weather that can affect humans and technology anywhere in the inner heliosphere are associated with solar particle events. Recent space weather research has shown that, in a worst-case scenario (W1), unprotected astronauts who are suddenly exposed to solar particle radiation in space can reach their permissible exposure limits within hours of the onset of an event. Such events are a direct effect of the rapid release of stored magnetic energy at active regions on the Sun.

Addresses Goal 1 (Determine the origins of the Sun's activity and predict the variations in the space environment)

Addresses Challenge SH-1 (Understand how the Sun generates the quasi-cyclical magnetic field that extends throughout the heliosphere)

Addresses Challenge SH-3 (Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate throughout the heliosphere)

The accurate prediction of the timing both of safe intervals and of sudden releases of radiation at the Sun poses a major challenge to the system science of heliophysics. The time scales involved span several orders of magnitude: minutes and hours are associated with high-energy particle propagation from the Sun to the Earth, days are associated with arrival of solar wind plasma, and months to years for the full development of the heliospheric consequences of solar explosive events.

The largest potential impact on exploration would derive from the ability to predict "all clear" periods. This capability could improve safety by optimized scheduling of manned launches and extravehicular activities. In recent years, several observational tools and methods have been developed and are currently being validated that would greatly improve forecasting. Early successes are (1) the capability to image active regions on the far side of the Sun with helioseismology; (2) the now-casting of light-speed particles from prompt particle events that can give up to a 1-hour warning of hazardous SEP arrival; and (3) heliospheric imaging that can give 0.5- to 2-days warning of the arrival of energetic storm particles and magnetic disturbances at distances where human and robotic explorers might venture. These advancements have improved our predictive capability. However, much remains to be understood that will enable a significant increase in warning times.

Successful forecasting of space weather depends on (1) the complete identification and observational coverage in real-time of critical solar disturbance parameters, (2) the development of observational tools and improved instrumentation that is alert and fully functional even in the midst of severe space weather, and (3) the advances in physical understanding (F and H) as a basis for theoretical and computational modeling of the Sun-Earth-inner heliosphere system, and (4) the development and improvement of models of the solar inputs that impact the Sun-Earth-heliosphere system. These are all necessary conditions for a heliophysics science enterprise that would fulfill its responsibility for NASA embarking on next-generation exploration activities.

W3: Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers

Mission success of a landing, on the moon or other body, depends on the productivity of astronauts or robotic explorers deploying instrumentation and collecting scientific samples in the surroundings of their landing sites. Solar activity can severely disrupt science activities for a period equivalent to the duration of a short mission, especially if the evolution of the solar event is not sufficiently predictable.

W3

Addresses Goal 1 (Determine the origins of the sun's activity and predict the variations in the space environment)

Addresses Goal 3 (Determine the interaction of the Sun with the solar system and the interstellar medium)

Addresses Challenge SH-3 (Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate throughout the heliosphere)

Addresses Challenge SWMI-2 (Identify the mechanisms that control the production, loss, and energization of energetic particles in the magnetosphere)

Addresses Challenge SWMI-3 (Determine how the coupling and feedback between the magnetosphere, ionosphere and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind)

The impact of space weather events on humans and technology in space critically depends not only on the intensity of the solar event but also on the site of interest in the solar system, the other properties of the outburst, and the characteristics of the pre-existing solar wind. CMEs, for example, propagate away from the slowly rotating Sun on a near-radial trajectory. Thus, whether or not the disturbance interacts with the Earth, Moon or other body depends mostly on the direction and width of the expanding CME.

The particle radiation environment in the heliosphere depends on the propagation and transport of the particles in the solar wind and on the radial evolution of, and interaction with, solar disturbances. The behaviors are complex. Some solar particle events can increase radiation intensity to critical levels very rapidly, others rather slowly or not at all. At times, two maxima can occur, both originating from a single solar event; and, in extreme events, the particles tend to fill the inner heliosphere.

Recent progress in heliophysics has been made to better characterize the extent of solar particle events through observations from distributed vantage points. However, the observational basis for these studies needs to be improved. Despite the value of remote sensing, the outer corona, which constitutes the interface between the inner corona and the solar wind, can only be fully understood with direct in situ measurements. In parallel with improved measurements, progress will also be made through the continued development and improvement of computational models of disturbances propagating from the Sun through the heliosphere to Earth, to other planets, and to planned spacecraft locations.

GCRs are modulated globally over the solar cycle but also locally through propagating transient disturbances. The outer heliosphere is thought to shield us from much of the nearly continuous GCR flux, perhaps by as much as 90 percent at a particle energy of 100 MeV/nucleon, although recent Voyager observations show that the barrier, if it exists, is not in the inner part of the heliosheath. The sensitivity of the GCR flux to approaching solar disturbances has provided a valuable tool for predicting space weather hazards for spacecraft.

W4: Understand, characterize, and model the space weather effects on and within terrestrial and planetary environments

Exploration activities are inherently risky. Beyond the technical challenges, the planetary plasma environments that respond to solar- and heliosphere-driven space weather will affect human and robotic explorers across the solar system. The "near-planet" radiation environment, applicable to Earth and all other planetary systems, is of particular concern for exploration activities as this is where exploration will take place for extended periods of time. Space weather at planets can intensify and restructure radiation belts. An effective strategy that minimizes the cumulative dose from increased radiation belt intensity is avoidance through advance warning. The key role that heliophysics occupies is to build a detailed understanding of the physical processes that create and drive the radiation environments near the Earth and other planetary bodies, and to develop the theoretical knowledge and quantitative models needed to predict how the geospace or near-planetary space environments will

Addresses Goal 2 (Determine the dynamics and coupling of the Earth's magnetosphere, ionosphere, and their response to solar and terrestrial inputs)

Addresses Goal 3 (Determine the interaction of the Sun with the solar system and the interstellar medium)

Addresses Challenge SH-3 (Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate throughout the heliosphere)

Addresses Challenge SWMI-2 (Identify the mechanisms that control the production, loss, and energization of energetic particles in the magnetosphere)

Addresses Challenge SWMI-3 (Determine how the coupling and feedback between the magnetosphere, ionosphere and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind)

Addresses Challenge SWMI-4 (Critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations from different magnetospheric systems)

Addresses Challenge AIMI-1 (Understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over global, region and local scales)

Addresses Challenge AIMI-2 (Understand the plasma-neutral coupling processes that give rise to local, regional, and global-scale structures and dynamics in the AIM system) respond to forcing from space-weather events. In the meantime, improved characterization of these environments and identification of parameters that indicate changes will reduce risk to exploration activities to the extent possible.

Existing models of the radiation belts derived from archived observations from early missions are of limited use for predicting radiation doses and exposure because the Earth's magnetic field magnitude and orientation has changed significantly in the decades since those observations were made. The newly developed models based on observations from recently launched missions will provide a more accurate and detailed understanding of the present and near-term state of the magnetospheric and ionospheric environments. Numerical simulations suggests that the evolving Earth’s magnetic field may be in part responsible for the apparent increase in solar geomagnetic storm occurrence during the last century. In addition, approximately 5% changes in the altitude and 10% changes in magnitude of peak ionospheric density may be attributable to changes in the Earth’s magnetic field.

Gradual changes in solar activity, solar wind, and extreme ultraviolet radiation also play significant roles in defining the longer-term variation of the geospace environment. Trends associated with all of these phenomena are convolved with those attributable to greenhouse gas increases and associated enhanced upper atmospheric radiative cooling, as well as changes in internal dynamical drivers. The evolving state of the IT system, combined with attribution to the underlying physical drivers, forms the basis of space climate research, a topic of emerging importance to basic and applied Heliophysics research.

The ionospheres, thermospheres, and mesospheres impact exploration activities in other planetary environments. These layers provide a means for long-range communication through ionospheric reflection of radio signals. However, surface-to-orbit and surface-to-surface communications are sensitive to heliophysical processes.

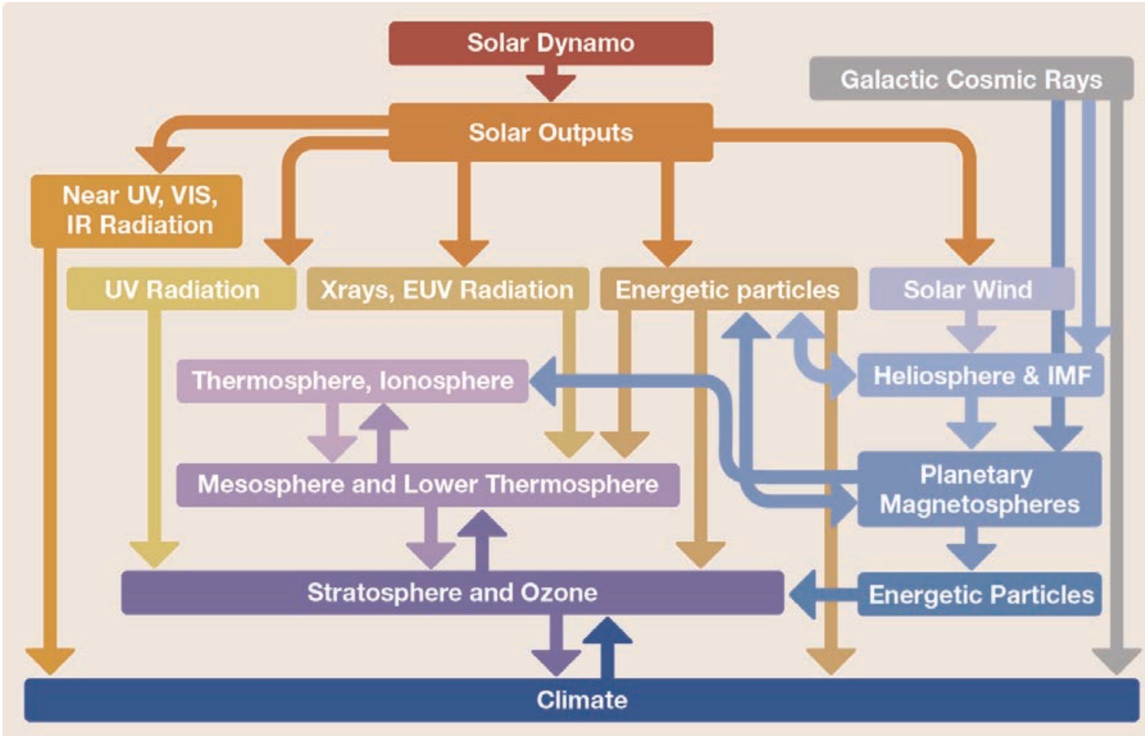
Aerobraking is a novel technique that utilizes the thermosphere and mesosphere instead of costly propellant. Spacecraft control in low orbits and in aerobraking parking orbits depend on the knowledge of upper atmosphere neutral density. Neutral density variability at aerobraking altitudes is partially controlled by dynamical influences from the planetary atmosphere.

Lunar dust interacts with the solar radiation and solar wind. The plasma and UV radiation environment at the Moon’s surface contributes to recognized problems with lunar dust. Dust grain adhesion on astronaut suits and instrumentation is not fully understood or resolved.

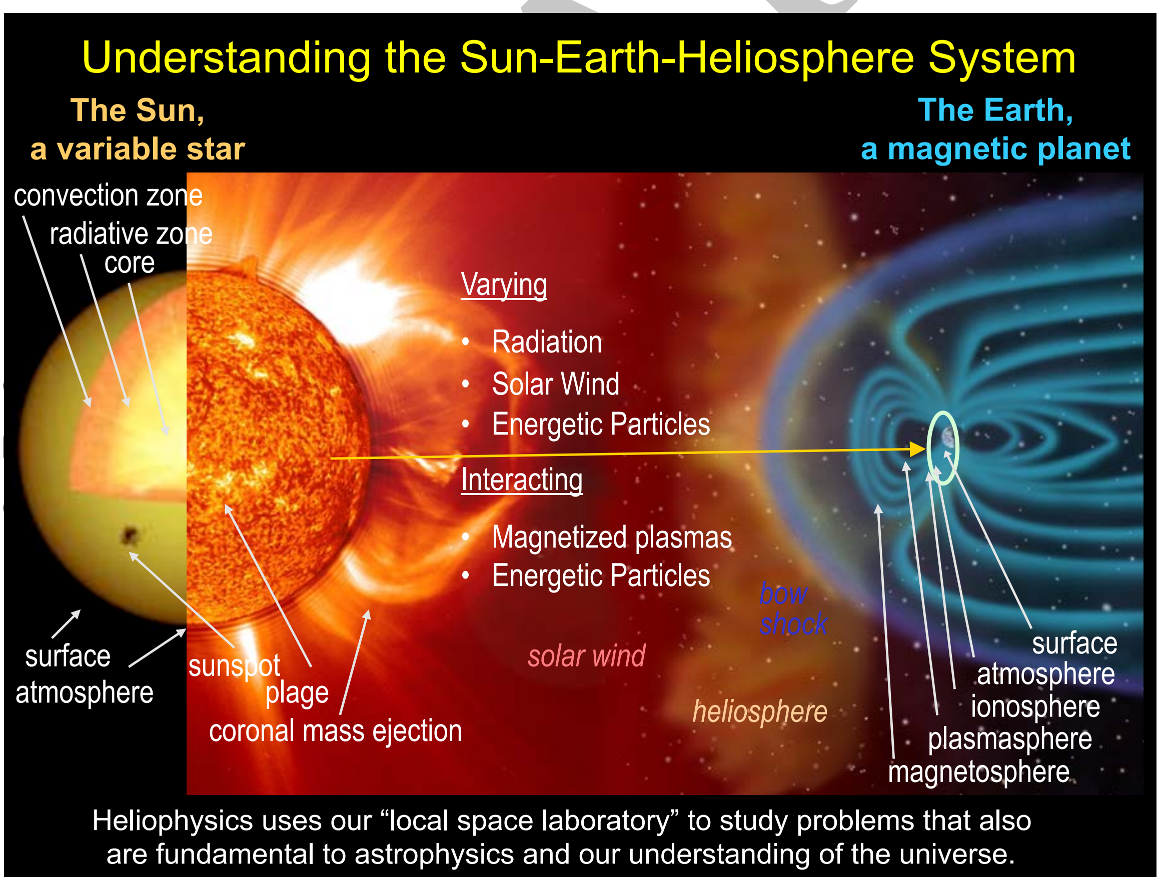
Heliophysics science reduces risk for exploration by directly addressing the above issues, through its current and planned missions. Heliophysics, as an interdisciplinary science, will potentially benefit from planetary exploration as the planets and the Moon hold unique archival clues on the distant past of solar terrestrial processes that will allow us to understand the system in more depth and detail. In parallel with improved data provided by Heliophysics missions, we must continue to develop and improve our ability to model the geospace and planetary space environments as they respond to forcing from within the Earth or planetary systems, as well as forcing by space-weather events.

Roadmap Objectives	Research Focus Areas
• ***Solve the Fundamental Mysteries of Heliophysics*****,** Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system	• Understand magnetic reconnection • Understand the plasma processes that accelerate and transport particles • Understand ion-neutral interactions • Understand the creation and variability of solar and stellar magnetic dynamos • Understand the role of turbulence and waves in the transport of mass, momentum, and energy
• ***Understand the Nature of our Home in Space***, Advance our understanding of the connections that link the Sun, the Earth, planetary space environments, and the outer reaches of our solar system	• Understand the origin and dynamic evolution of solar plasmas and magnetic fields throughout the heliosphere • Understand the role of the Sun and its variability in driving change in the Earth's atmosphere, the space environment, and planetary objects • Understand the coupling of the Earth's magnetosphere-ionosphere-atmosphere system, and its response to external and internal forcing • Understand the nature of the heliospheric boundary region, and the interactions between the solar wind and the local interstellar medium
• ***Build the Knowledge to Forecast Space Weather Throughout the Heliosphere***, Develop the knowledge and capability to detect	• Characterize the variability, extremes, and boundary conditions of the space environments that will be

and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth	encountered by human and robotic explorers • Develop the capability to predict the origin, onset, and level of solar activity in order to identify potentially hazardous space weather events and all-clear intervals • Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers • Understand, characterize, and model the space weather effects on and within terrestrial and planetary environments



Solar Dynamo
Galactic Cosmic Rays
Solar Outputs
Near UV, VIS, IR Radiation
UV Radiation
Xrays, EUV Radiation
Energetic particles
Solar Wind
Thermosphere, Ionosphere
Heliosphere & IMF
Mesosphere and Lower Thermosphere
Planetary Magnetospheres
Stratosphere and Ozone
Energetic Particles
Climate



Understanding the Sun-Earth-Heliosphere System
The Sun, a variable star
The Earth, a magnetic planet
convection zone
radiative zone
core
Varying
Radiation
Solar Wind
Energetic Particles
Interacting
Magnetized plasmas
Energetic Particles
bow shock
solar wind
heliosphere
surface atmosphere
sunspot
plage
coronal mass ejection
surface
atmosphere
ionosphere
plasmasphere
magnetosphere
Heliophysics uses our "local space laboratory" to study problems that also are fundamental to astrophysics and our understanding of the universe.

Chapter 2: Recent Highlights of the Discipline

Introduction

Earth is best understood not as orbiting the Sun in isolation through a vacuum, but as a physical system connecting the magnetized solar atmosphere and Earth's magnetosphere, ionosphere, and neutral atmosphere. Earth resides in the outer atmosphere of the Sun, which emits a constant solar wind. The Sun occasionally sends out powerful mass ejections, accompanied by shock waves that accelerate charged particles to nearly the speed of light. These disturbances drive the aurora and powerful electric currents on Earth, and violently churn the ionosphere and uppermost atmosphere.

There is a growing appreciation that solar systems are commonplace in the universe and that the physical processes active in our heliosphere are widespread. Deepening understanding of our own home in space therefore informs humanity's understanding of some of the most basic workings of the Universe. As human exploration extends further into space via robotic probes and human flight, and as society's technological infrastructure becomes increasingly linked to assets that are impacted by the space environment, a deeper and fundamental understanding of these governing processes becomes ever more pressing.

During the decade of 2003 – 2012, dramatic advances were made in establishing the relationships between solar activity, resulting interplanetary disturbances, the response of Earth's space environment, and the dynamics of the outer boundaries of our solar system with interstellar space. These developments occurred in coordination with advances in physics-based numerical simulations that provide the foundation for understanding phenomena in terms of underlying physical processes, and attaining a measure of predictive capability. Scientists in heliophysics are now poised to answer questions concerning universal physical processes, to advance understanding of the complex coupling and non-linear dynamics of our home in the solar system, and to apply this understanding to mitigate the societal impacts of changes to our space environment by identifying and forecasting the threats posed to technological infrastructures.

A selection of the most salient discoveries and advances are presented here, organized by the science objectives and the RFAs articulated in Chapter 1. These science highlights provide the context for understanding how the recommendations of the Decadal Survey and the Roadmap Team follow from the flow of scientific discovery.

F Solve the Fundamental Mysteries of Heliophysics

The Sun, our solar system, and the universe consist primarily of plasma. This section highlights recent developments in understanding the collective behavior of the plasma state, and its interaction with the neutral gas in planetary atmospheres.

Magnetic reconnection is a ubiquitous process in plasmas in which magnetic field lines break and reform causing plasma energization by magnetic field annihilation. Over the last decade, the missions Cluster, and Wind have shown that this process actually takes place within very small-scale regions, which shift in location rapidly and are thus difficult to pinpoint in the vastness of space.

Wave–particle interactions (WPI) are key drivers of particle energy gain and loss in the radiation belts. The mixing of energetic and low-energy plasmas drives instabilities throughout the inner magnetosphere, where different plasma populations are commingled. On August 30, 2012, NASA launched the twin spacecraft called the Van Allen Probes with identical energetic particle, plasma, magnetic field, and plasma wave sensors. These devices provide unprecedented detection sensitivity, energy resolution, and temporal sampling capability for measuring the radiation belt regions. Their measurements reveal very detailed spatial and temporal characterizations of multi-MeV electron populations, further suggesting the vital roles of WPI to the radiation belts.

An important element of the dynamics of the IT system is the transfer of energy and momentum between the plasma and neutral components of the system. These processes are fundamental to space physics, as they occur at all planets with atmospheres, comets, and within the magnetospheres of Jupiter and Saturn. During the most recent solar minimum, when thermospheric densities dropped to their lowest recorded levels, the ionosphere nevertheless displayed a surprising array of dynamics. Complex density structures occurring near local dawn were documented by the USAF C/NOFS mission and NASA CINDI experiment and other space and ground-based assets including DMSP instruments and the NASA TIMED mission. It is now known that a quiet Sun does not correspond to a calm, benign ionosphere and that deleterious impacts to navigation and communications occur under these conditions in, as yet, unexpected ways. Figure 3 illustrates how neutrals in the lower atmosphere, in this case the response to a sudden stratospheric warming (SSW) event changes total electron content (TEC) at low latitudes. SSWs are observed at high latitudes in the stratosphere; the mechanism for the connection between the high-latitude stratospheric neutrals and the equatorial ions remains to be elucidated.

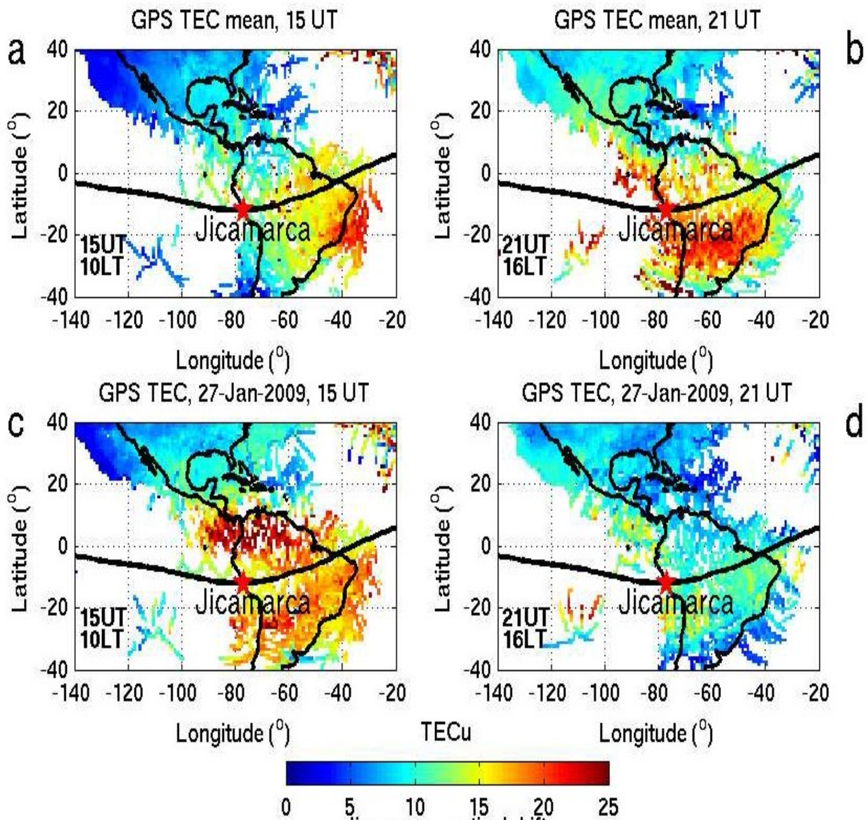


Figure 3: Equatorial ionospheric response to sudden stratospheric warming (SSW). The ionosphere changes in response to variations in the vertical drift. The upper panels show mean behavior in the Total Electron Content (TEC) for 15 UT (morning sector) and 21UT (afternoon sector) on 27 January 2009 during an SSW. Lower panels show how TEC looks during SSW: it is strongly increased in the morning and decreased in the afternoon and shows a semidiurnal pattern in large range of latitudes.

The interface between the solar interior and the corona is a complex, highly structured and very dynamic region called the chromosphere, consisting of both ionized plasma and neutral gas. The detailed structure and dynamics of the chromosphere play a large role in defining how energy is transported into the corona and solar wind. Solar differential rotation in the turbulent solar convection zone is the most likely source for the energy that heats the solar corona and powers the outflows and waves present in the solar wind. Recent observations of spicules in the solar chromosphere by the joint JAXA/NASA Hinode mission may be the source of mass and energy for the corona and solar wind.

H: Understand the Nature of Our Home in Space

To better understand our place in the solar system, we investigate the interaction of the space environment with the Earth, and its effects on technology and society. Earth's space environment is ultimately regulated by the outflow of plasma, energetic particles, and electromagnetic radiation from the Sun. Understanding the origin and dynamic evolution of the solar plasma and magnetic fields throughout the heliosphere provides the essential foundation to build predictive models, based on physical principles, of the Earth's space environment. This section highlights developments in these predictive capabilities.

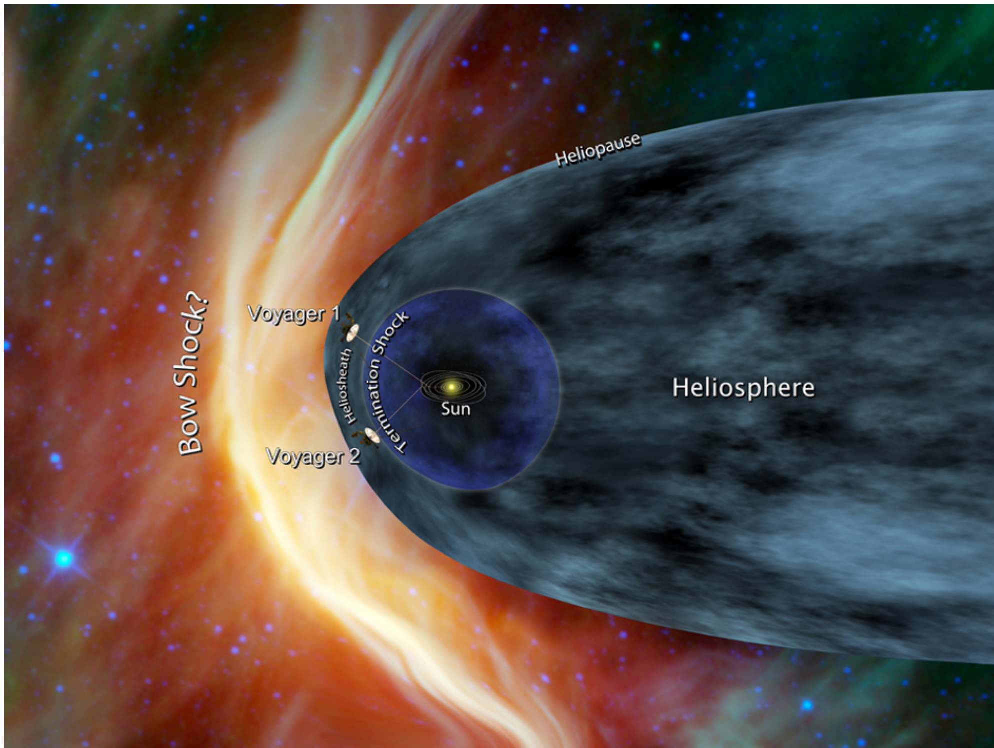
Understanding and predicting the evolution of coronal mass ejections (CMEs), energetic particle populations, and turbulent electromagnetic field and plasma fluctuations flowing outward through the heliosphere remains a significant scientific challenge. High resolution images of the dynamics in the solar atmosphere such as SDO's Helioseismic and Magnetic Imager (HMI) vector magnetograms and of solar spicules observed by Hinode's Solar Optical Telescope (SOT) coupled with three-dimensional MHD numerical models of the coronal dynamics are making significant progress towards achieving closure between observations and theoretical models.

A leading development in recent years is the understanding that tropospheric weather and climate can strongly affect the upper atmosphere and ionosphere. The release of greenhouse gases (e.g. CO_2 and CH_4) into the atmosphere is changing the surface climate by warming the lower atmosphere, and by cooling the upper atmosphere. A systematic decrease in thermospheric mass density has been inferred from the record of satellite orbit decay measured since the beginning of the space age. Continued cooling of the thermosphere will reduce satellite drag, thereby increasing orbital debris lifetimes, and lower the effective ionospheric conductivity. The latter will alter global currents in the magnetosphere–ionosphere system and therefore fundamentally alter magnetosphere–ionosphere coupling. Changes in tropospheric weather patterns and atmospheric circulation may alter the occurrence of ionospheric instabilities triggered by tropospheric gravity waves propagating into the upper atmosphere; this will affect the prevalence of the resulting ionospheric irregularities.

As our Sun moves through the local interstellar medium (LISM), the outflowing solar wind carves out a cavity known as the heliosphere, which protects us from harmful galactic cosmic radiation. Since its launch in October 2008, the Interstellar Boundary Explorer (IBEX), with its two energetic neutral atom (ENA) cameras, has provided humankind with the first ever global images of the complex boundary separating the heliosphere from the LISM, and revealed a mysterious ribbon of intense ENA emissions apparently ordered by the interstellar magnetic field (ISMF), and superposed on a global background of ENA emissions emanating from beyond the solar wind termination shock.

IBEX also measures various constituents of the neutral interstellar gas that flows directly into the inner solar system and hence yields important clues about the properties of the LISM. These new measurements enabled us to infer the interstellar speed and location of our Sun more precisely than before. Our solar system actually resides in the local cloud rather than at its edge, and moves through it at 52,000 miles per hour, roughly 7000 miles per hour slower and in a somewhat different direction than that inferred from previous measurements. With the local interstellar magnetic field strength now being determined to be somewhat larger than previously thought, IBEX measurements imply that our slower heliosphere is only able to create a broad bow wave instead of a bow shock as it ploughs through the interstellar medium.

The Voyager 2 spacecraft provides direct measurements of particles, plasmas, and magnetic fields in the heliosheath (the boundary region between the heliosphere and the interstellar medium). Voyager 1 has entered interstellar space, becoming the first human-made object to leave the heliosphere and communicate its findings back to Earth. These new observations from IBEX and Voyager have forced a reexamination of our understanding of the location and nature of our heliosphere's interaction with our galactic environment, which will ultimately lead to a better understanding of how the galactic cosmic rays enter and penetrate deep into the solar system.



W: Build the Knowledge to Forecast Space Weather throughout the Heliosphere

Both human and robotic exploration brings challenges and hazards. We need to help safeguard these space journeys by supporting the development of predictive and forecasting strategies for space environmental hazards.

Magnetic flux ropes in the solar atmosphere are known to store magnetic energy, which can later be released as flares, CMEs, and associated solar energetic particles (SEPs). Such direct observations take us a step closer to predicting eruptive events, a major source of space weather. Figure 9 shows first observations of the actual formation of a kinked magnetic flux rope at the heart of the explosive release of a CME on 19 July 2012. As theorized, the flux ropes look like a series of figure eights. However, the foot points were more widely separated than anticipated, requiring further study.

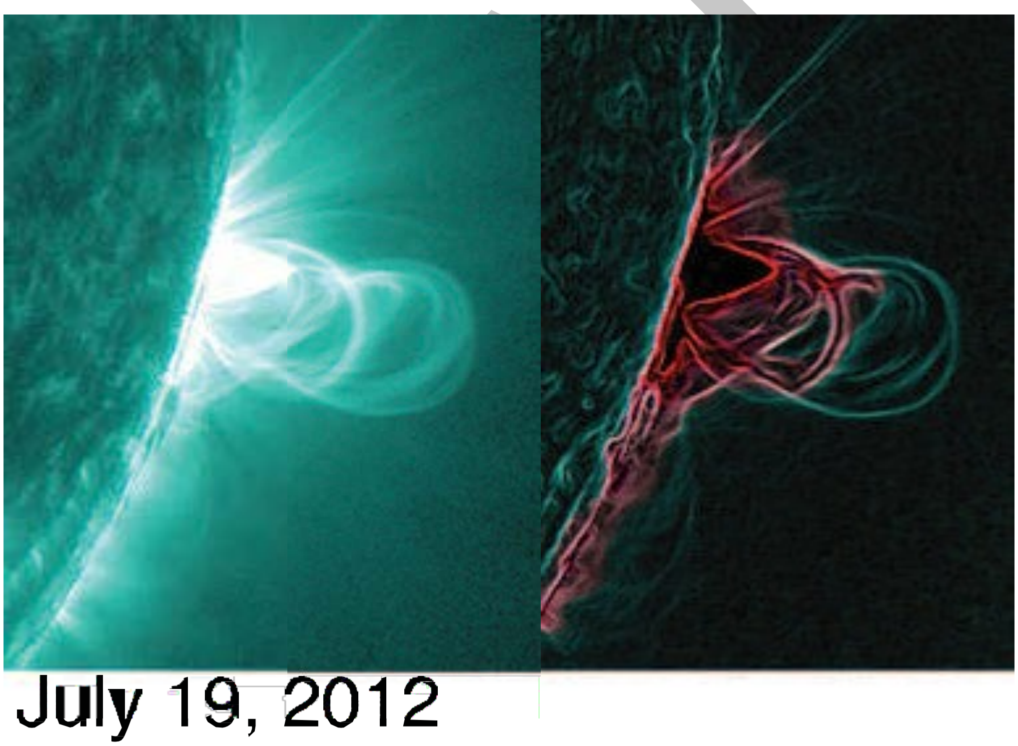


Figure 9: Formation of a core flux rope in a CME. Photo credit: NASA/SDO/GSFC.

SEP events are a major radiation hazard for spacecraft and astronauts. Most large SEP events are not only associated with a large flare but also have a recent, preceding CME from the same active region. The discovery that relativistic electrons provide about a 1-hour warning of arriving SEP ions has provided a new forecast tool. A major discovery showing how the SEPs and solar disturbances in general, influence the near-Earth environment was achieved by the recently launched Van Allen Probes (formerly known as the Radiation Belt Storm Probes).

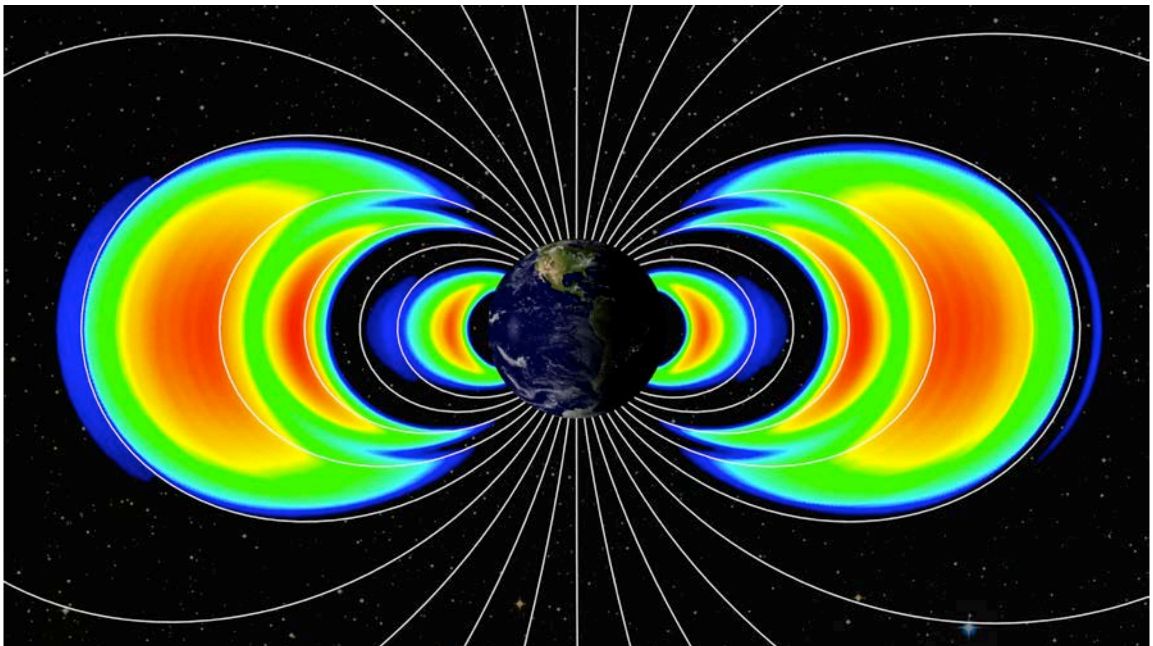


Figure 10: Radiation belt observations (yellow/orange regions). (NASA/Van Allen Probes/GSFC.)

Shortly after launch on August 30, 2012, the Van Allen probes observed the formation of a third radiation belt (Figure 10), which persisted for four weeks before being destroyed by the arrival of another interplanetary shock. In the image the yellow/orange regions represent the belts. Green shows the space between the belts. Apparently, the belt particles are accelerated by electric fields within the belt region. Further analyses are underway. The discovery shows the dynamic and variable nature of the radiation belts and improves our understanding of how they respond to solar activity.

The radiation belts are an important part of a larger space weather system that stretches from the Sun to Earth and beyond. The belts absorb energy and particles from the Sun and so can harm space assets that pass through the radiation belt region. The belts can also pass energy on to Earth's atmosphere in ways that can, in extreme cases, disrupt our communications systems or electric power grids. In addition, it is suspected that energy from the radiation belts affect the composition of Earth's atmosphere and ozone layer.

Chapter 3: Heliophysics Landscape:

Studying the Sun, the heliosphere, and other planetary environments as an interconnected system is critical for understanding the implications for Earth and humanity as we venture forth through the solar system. To that end, the NASA Heliophysics program seeks to perform innovative space research missions to understand: (1) the Sun and its variable activity; (2) how solar activity impacts Earth and the solar system; and (3) fundamental physical processes that are important at Earth and throughout the universe by using space as a laboratory. Heliophysics also seeks to enable research based on these missions and other sources to understand the connections among the Sun, Earth, and the solar system for science and to assure human safety and security both on Earth and as we explore beyond it.

The *2014 NASA Strategic Plan* outlines the following science goals for the Agency:

- Expand the frontiers of knowledge, capability, and opportunity in space
- Advance our understanding of our home planet and improve the quality of life
- Serve the American public and accomplish our Mission by effectively managing our people, technical capabilities, and infrastructure

The Heliophysics strategic objective, "Understand the Sun and its interactions with Earth and the solar system, including space weather" falls under the first Agency goal. This chapter describes the strategies, opportunities, and challenges that the HPD has identified to shape the plans for progress. The strategies are long-range in nature but adapt to changing national goals, new scientific understanding and technologies, and evolving Agency policies. The challenges span all timeframes and SMD must continuously look for every opportunity to address them.

Through the Strategic Objective Annual Review process, the HPD has developed the following strategies for addressing the science objectives:

- Ensure that strategic decisions for future missions and scientific pursuits are informed by national priorities and guided by priorities recommended in the NRC Heliophysics Decadal Survey, to the extent feasible, given budget environment and opportunities for partnership
- Actively engage the research community beyond NASA to establish science priorities, prepare and review implementation plans, analyze requirements and trade studies, conduct research, and evaluate program performance
- Make investment choices based on scientific merit via peer review and open competition, with selected activities directed on a limited basis in order to maintain critical capabilities
- Maintain a balanced portfolio of space missions and mission-enabling programs

- Implement effective program/project management processes to ensure successful implementation and operation of Heliophysics related programs within planned cost and schedule resources.
- Maintain robust international, intra-agency, interagency, academic, and private partnerships
- Provide rapid, open access to data to enhance the pace of scientific progress
- Provide broad public communication regarding programs and scientific discoveries

There are challenges that Heliophysics faces in implementing its science plan. The Heliophysics Division faces all the challenges articulated in 2014 NASA SMD Science Plan, including: access to space, mission cost estimation and management, technology development and demonstration, impediments to international collaboration, protecting the planet while advancing science (particularly with respect to space weather), unstable budget environment, workforce development, and unrealized expectations. In particular, a flat or declining budget combined with increasing costs associated with access to space, have resulted in a tightly constrained fiscal environment in Heliophysics. We remain committed to implementing a balanced mission portfolio that provides the vitality needed to accomplish the breadth of the recent Decadal Survey's science goals within the limitations of our available resources.

In addition, Heliophysics addresses system science that depends on coordinated observations made possible by the fleet of spacecraft that is made up of various scientific research missions, many of which are operating well beyond their design lifetimes. Maintaining and expanding the HSO requires continuing financial support, creating a natural conflict between continuing existing missions and other areas of the budget. In the coming years, Heliophysics will be even more challenged by demands to provide the long-term and continuous observations necessary to understand the systemic nature of Heliophysics science.

The need for the connected measurements underscores the criticality of maintaining an adequate mission cadence and balance. Heliophysics will pursue multiple approaches to optimize the cadence by 1) applying of state-of-the-art technologies to meet science goals at reduced expense, 2) exploring the value of missions with full life-cycle costs below the current standards, 3) leveraging domestic and international partnerships for missions and launch vehicles, and 4) adjusting scope of the planned missions. The continuity of missions is key; without continuity, the opportunities provided by the simultaneous operation of the HSO missions and the new missions discussed here, will be lost.

In order to meet these challenges, one of the most effective tools is partnerships. Partnerships with other national and international agencies and within NASA provide opportunities to meet shared science goals. When the Heliophysics Division teams with other organizations the opportunities for addressing its scientific goals are increased dramatically. Our science is cross-disciplinary, practical and international, leading to partnership opportunities within SMD, within NASA, with other agencies and with other space-faring nations. Taking advantage of every opportunity will provide for a robust and cost effective flight program. Within NASA, there are important synergies between Heliophysics objectives and those in Astrophysics, Planetary, and Earth Sciences, which should be exploited. Heliophysics has a long history of collaborations with

Planetary Science Division missions. LADEE, MSL, MAVEN and JUNO are examples of missions with Heliophysics instrumentation. Other important measurements from the Planetary Division are the solar wind measurements at Pluto from the New Horizons mission. Collaborations with Exploration Systems Mission Directorate (ESMD) is more recent through Lunar Reconnaissance Orbiter (LRO) program. The ISS offers rich possibilities for remote sensing of the ionosphere and the Sun.

The scientific and programmatic objectives of the NASA Heliophysics program enjoy strong synergies with NSF, DOD, DOE, and Department of Commerce, NOAA. The teamwork between the U.S. and other space agencies augments the capabilities of many Heliophysics science missions and permits investigations that could not be achieved separately. Beyond NASA, interagency coordination in space weather activities has been formalized through the National Space Weather Program Council, which is hosted by the Office of the Federal Coordinator for Meteorology. This multiagency organization is comprised of representatives from ten federal agencies and functions as a steering group responsible for tracking the progress of the National Space Weather Program. External constituencies requesting and making use of new knowledge and data from NASA's efforts in Heliophysics include NOAA, DOD, and the FAA. Examples include the real-time space weather data supplied by the ACE, STEREO, SOHO, SDO, and Van Allen Probes missions. Other partnerships include the Coupled Ion-Neutral Dynamics Investigation (CINDI) instrument supplied to the Air Force C/NOFS satellite, and the Two Wide-angle Imaging Neutral Atom Spectrometers (TWINS-A & B) provided for two National Reconnaissance Office satellites. NASA will continue to cooperate with other agencies to enable new knowledge in this area and to measure conditions in space critical to both operational and scientific research. Additionally, leveraging resources across multiple agencies allows for timely advancement of the science that would not otherwise be possible. NASA and NOAA have cooperated on providing a follow-on capability at L1, DSCOVR. This mission will provide critical space weather information for science, commercial, and military applications.

International partnerships have long played and promise to continue to play an extremely important role in addressing the heliophysics science imperatives in a highly leveraged and extraordinarily cost-effective manner. During times of constrained budgets it is critical for Heliophysics to foster and participate in joint missions. Jointly developed missions such as Ulysses, Yohkoh, SOHO, Cluster, and Hinode are all examples of successful collaboration and have significantly advanced heliophysics science. Strengthening the scientific and technical teamwork between the US and our partners permits activities that could not be achieved separately.

In some cases, international partnerships can represent both an opportunity and a risk. For example, HPD is partnering with the European Space Agency (ESA) on the Solar Orbiter mission. NASA is providing two instruments and the launch vehicle for the mission, with ESA and member states providing the components of US instruments, the spacecraft and additional instruments. The risk to NASA is late delivery of the interfaces needed to complete the instruments and late delivery of the completed satellite for launch. Both events could have cost impacts.

Strength Weaknesses Opportunities and Threats (SWOT) Analysis

In assessing the future direction of heliophysics research as a discipline, it is prudent to candidly consider the strengths, weaknesses, opportunities, and threats (SWOT) in the heliophysics landscape. For this analysis, we considered *internal* attributes to be those that exist within the HPD and/or heliophysics community, while *external* conditions are those that exist outside or beyond (but may be internal to NASA as an Agency). Strengths and weaknesses relate to internal factors, while opportunities and threats are external to heliophysics.

With this analysis, we found the HPD to currently be productive, but facing future funding shortages. Our efforts to integrate with other agencies are only partially successful. Significant weaknesses and threats to the enterprise do exist and must not be ignored for successful execution of the Heliophysics program. The budgetary constraints under which this roadmap was produced are very severe. In the coming years, the HPD must be extremely agile to identify opportunities and mitigate threats. The implications of even modest cost growth in the current flight program will be profoundly adverse.

The context for Strengths Weaknesses Opportunities and Threats (SWOT) analysis is our priorities, which are derived from the Decadal Survey:

- Complete the current missions with a commitment to maintaining cost and schedule.
- Initiate the DRIVE program as an augmentation to the existing research program.
- Execute a robust and enlarged Explorer program including leveraged Missions of Opportunity (MO) and low cost options.
- Launch strategic missions in the STP and LWS lines.

Strengths of HP Program:

1. Our fundamental science is at the core of science in all of the other SMD divisions. Heliophysics science has broad importance and applicability. Progress in our science is readily transferred to other divisions.

2. Our systems science leads to physics-based improvements of space weather predictions in geospace and throughout the heliosphere. Progress on understanding the scientific basis for space weather prediction will form the basis for new forecasting models and new operational requirements in the space weather community.

3. Many critical science goals can be accomplished with a robust Explorer program and moderately sized STP missions. The risks associated with cost growth are reduced as the overall mission costs are lower.

4. The Heliophysics Systems Observatory consists of many missions, and is therefore intrinsically robust.

Weakness of the HP Program:

1. Maintaining the HSO requires substantial resources. This places a natural conflict between continuing existing missions and all other areas of the budget.

2. Cost growth within the flight programs must be contained. Final allocations for missions are not confirmed until Key Decision Point (KDP) C (See Figure 13), several years into the mission. Before that time, there is only the accepted proposal budget. The community needs to contain cost growth on both sides of KDP-C. This may result in significantly larger reserves, which means that the resulting instrumentation is less capable.

3. The breadth of our program is both a strength and a weakness. Heliophysics subdisciplines have notable differences as reflected in their distinct professional society meetings, scientific journals, data archiving approaches and data processing systems. The community must actively work to overcome cultural differences so that they remain a strength and not a weakness.

4. Inter-disciplinary science is both a strength and a weakness. Working across discipline boundaries is necessary to address critical aspects of our science. This requires the analysis of data from multiple spacecraft (often in different formats and with different analysis packages). It requires joining models across interfaces that are time dependent, difficult to constrain and inherently complex. It requires reaching out to scientists who have spent years specializing within a single discipline.

Opportunities for the HP Program

1. Significant progress can be made with low-cost Explorers, MOs, new capabilities on the International Space Station (ISS) and with smallsats and CubeSats of various sizes.

2. A well-crafted program will dramatically improve our understanding of the space environment in order to improve space-weather predictive capabilities.

3. Successful cooperation with other agencies will allow the programs to grow, leading to the development of operational satellites that will further advance the science of prediction.

4. Educating the next generation of heliophysicists in order to ensure that early career scientists are agile enough to cross traditional discipline boundaries. Our LWS summer schools and text books are an excellent starting point.

5. Re-prioritizing the HP budget as reflected in Figure 6.3 can occur nearly independently of HP budget size. This will help strengthen the program if the decision rules (pg 6-8) are followed.

Threats to the HP Program

1. The flat NASA budget projections result in HPD having ≈ $100M/yr less funding in 2024 compared with the Decadal Survey Report. It is not possible to implement a functioning strategic LWS flight program with these budget assumptions and the mission sizes suggested by the Decadal Survey.

2. Launch vehicles cost, availability and predictability continues to threaten the flight program. Progress has been made in this area in recent years.

3. Inter-agency communication is time consuming and difficult when staffing levels are strongly constrained by tight budgets. Insufficient communication results in inefficiencies that we cannot afford.

4. Unreasonable expectations – the goals of HPD must be consistent with the resources available. Promising to address the most challenging problems without adequate resources for missions and research will result in a perception of failure.

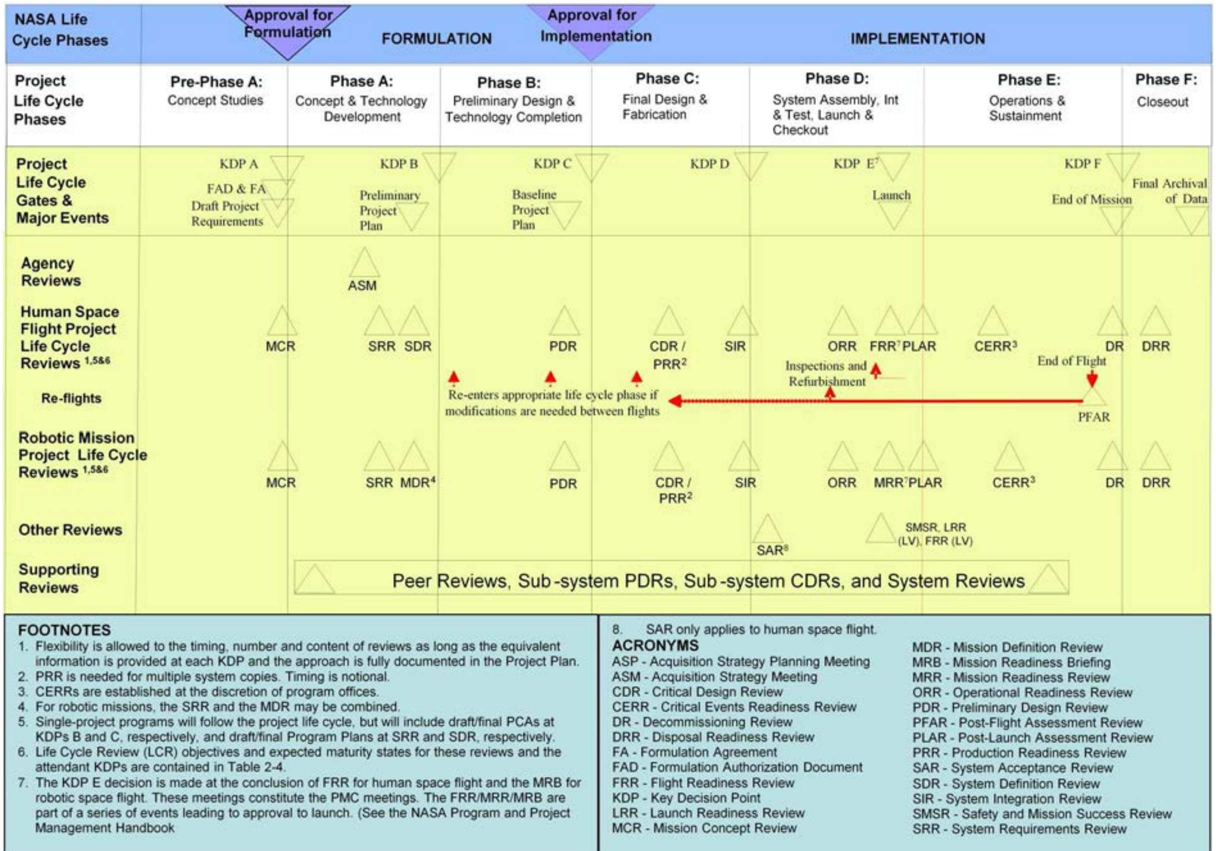


Figure XX: Relationship between mission phases, Key Decision Points and Reviews.

New Approaches for Mission Planning and Implementation

In order to implement the science program outlined in this Roadmap, the HPD needs to control cost growth and schedule slips in its flight programs (Explorer, STP and LWS mission lines). Cost growth in the flight programs are not a new problem, or unique to the HPD. Over the past 5 years several approaches have been suggested and implemented. Specifically, to better control mission cost estimation and management, NASA has transformed the management of programs and projects, acquisition strategies, and procurements, particularly for the most complex science missions. In particular, they have strengthened program and project management, established more rigorous cost estimation practices, gathered numerous external and internal cost estimates, and incorporated multiple, formal decision points as gates to the next stage of development. Continued attention to the problem throughout the HPD, by the Heliophysics Subcommittee and by the Management Operations Working Groups (MOWGs) is needed to evaluate what is working and what needs to be changed. The cost growth suggestions outlined here reflect suggestions from the Decadal Survey report (DS), the 2009 Roadmap, the Science Mission Directorate and NASA Advisory Council's Heliophysics Subcommittee.

1. Planning strategic missions in a way that allows for flexible solutions. Both the 2009 Roadmap and the DS argue for a mission planning approach that articulates the critical science goals and identifies candidate ways of achieving the goals without dictating the details of the mission profile. The intent is to identify the most pressing science goals that can be achieved within the available resources. Knowing that a mission profile will fit in a strategic mission box requires a costing exercise that assumes a particular orbit, instrument complement, data rate and lifetime. The challenge to our community is to continue to view the mission profile as notional after the detailed study has been done. Providing those responsible for implementing the program with the flexibility to address the science goals in a way that may be fundamentally different from the notional mission is key to this cost control element.
2. Identifying cost growth early in a mission is critical to being able to take corrective action before the growth has a large impact on the flight program schedule and on the non-flight research programs. Figure 12 shows cost history for SMD missions (over the past TBD years). SMD has implemented several cost control strategies to address the cost growth problems shown in Figure 12. Specifically, new guidelines have been established in NPR 7120.5E (NASA Space Flight Program and Project Management Requirements). In order to follow the reporting and review thresholds in the SMD process it is important to know the mapping of Key Decisions Points (KDP) to mission phases and reviews. Figure XX shows the mapping for nominal Heliophysics Robotic Mission Projects Life Cycle Reviews. At KDP-B (start of Phase B) the cost and schedule range is established. At KDP-C (after preliminary design review, PDR, start of Phase C) the 70% joint cost and schedule confidence level (JCL) is established, the directorate and project level reserves are identified along with any required unallocated future expenses (UFE) that are held above the management baseline. When a mission exceeds the growth levels, mandatory reporting and reviews are invoked. A mission exceeding the 30% Life Cycle Costs (for those over $250 million) will be subject to a termination review.

3. To establish the 70% JCL, management tools are needed. Earned-Value Management is the primary tool for program performance reporting and performance prediction. The Launch Readiness Date (LRD) is established along with the cost limits as part of the JCL.

4. When a mission exceeds its cost envelope, the implications for future missions and the research budget can be severe. The Decadal Survey has outlined a set of decision rules that should be applied to the HP budget under this circumstance (pages 6-9):

   (a) Missions in the STP and LWS lines should be reduced in scope or delayed to accomplish higher priorities.

   (b) If further reductions are needed, the recommended increase in the cadence of the Explorer missions should be reduced, with the current cadence maintained as a minimum.

(c) If further reductions are needed, the DRIVE augmentation profile should be delayed, with the current level of support for elements in the NASA research line maintained as the minimum.

Cost containment of strategic missions

The Roadmap Team believes that cost-capped, PI-led missions provide a strong method for curbing mission growth. Specifically, by having the direct involvement of the PI in shaping the decisions and the overall mission approach to realizing the science objectives, combined with the new NASA cost containment policy, it is anticipated these missions can be extremely cost effective. For moderate cost missions (~$500M), the Roadmap endorses the Decadal Survey recommendation that mission requirements, capabilities, and designs be competitively selected at the time of procurement. The Roadmap recommends that NASA engage in further study of the associated implication that “competitively selected” equates to “PI-led” in the same manner that it does for Explorer or Discovery program missions. At the conclusion of this study, NASA should, in consultation with its advisory groups, use the study findings to set a mission acquisition policy that best fulfills both the intent of the Decadal Survey recommendations and NASA’s programmatic obligations.

Chapter 4: Heliophysics Program Elements

To achieve the science objectives of the HPD, this roadmap recommends a strategy that leverages all HPD program elements. The recommendations include an integrated initiative that maximizes the science return by encouraging extensive use of our current assets in space – the Heliophysics System Observatory. The recommendations also include new missions to be deployed by the Explorer, Solar Terrestrial Probes (STP), Living With a Star (LWS), and Explorer flight programs. This roadmap recommends, as the highest priority, substantial investment in the research program including theory and modeling as well as technology development and suborbital opportunities. These programs provide the intellectual and technical foundation for the flight missions. For each of these program elements, we discuss how they address the open science questions flowing from the science goals of the research focus areas (RFAs) outlined in Chapter 1.

Heliophysics Program Elements

The Heliophysics Program Elements are: the Heliophysics System Observatory; Explorer, Solar Terrestrial Probes, and Living with a Star flight programs; and the Research program, including sub-orbital experiments and technology development. All are necessary for the development and unification of scientific understanding of the Heliophysics system. Partnerships with other national and international agencies, and within NASA, provide key additional opportunities to meet Heliophysics science goals by sharing costs, although significant issues such as specific funding for cooperative missions, data access and technology transfer issues must be addressed.

This chapter defines each of the funded program elements and shows how the outstanding questions can be addressed through judicious use of those elements. The description begins by reviewing the currently operating missions and the missions in development and the open questions currently being addressed. Next, the four highest-priority, unaddressed strategic science targets within the STP and LWS strategic flight programs are outlined. The assessment continues by reviewing the science that cannot be addressed within the strategic mission budget provided. It is clear that a robust Explorer mission line will be required in order to maintain current capabilities and enable the field to continue to make significant advances in our understanding. The challenges associated with meeting the science objectives associated with a compromised cadence of new STP, LWS, and Explorer missions is overtly discussed. That cadence is compromised by projected HPD budget constraints through FY2019. As detailed below, this Roadmap underscores the criticality of mission frequency and recommends that the HPD pursue multiple approaches to ensure a viable cadence by 1) applying of state-of-the-art technologies to meet science goals at reduced expense, 2) exploring the value of missions with full life-cycle costs below the current standards, 3) optimizing domestic and international partnerships for missions and launch vehicles, and by 4) adjusting scope of the planned missions The continuity of missions is key: without it the opportunities provided by the simultaneous operation of aging HSO elements and the new experiments discussed here, will be lost. The relationship of all of these missions to the Science

Traceability Matrix (see Appendix E) is a key element in the logical framework of the roadmap. Descriptions of current missions are found in Appendix C.

The chapter concludes by describing the broad range of supporting research activities that are needed to advance the state of our knowledge and provide the intellectual foundation critical for future flight missions. Advancing our understanding of the processes that shape the impact of the Sun on our Earth requires a robust presence in space: the Heliophysics Roadmap must provide an executable plan for maintaining that presence to the extent possible given the available resources. Making the greatest scientific use of data from existing missions is cost effective. For this reason the Roadmap recommends that the supporting research and technology programs be funded at a level that allows for full exploitation of the missions in which we have already made substantial investment.

The Heliophysics System Observatory (HSO)

The Roadmap Team recognizes that the study of heliophysics has progressed beyond the point where each sub-discipline should be considered in isolation. To make that next step, the HSO must be transformed into an integrated environment that enables interdisciplinary heliophysical science across the vast spatial scales of our solar system.

The HSO is a construct that utilizes the entire fleet of NASA solar, heliospheric, geo-space, and planetary spacecraft as a distributed observatory to discover the larger scale and/or coupled processes at work throughout the complex system that makes up our space environment. The synthesis of two or more missions results in capabilities beyond the sum of the individual missions. Ultimately, the combination of new heliophysics knowledge and a well-supported HSO can facilitate the path towards understanding fundamental physical processes that will improve space weather predictions.

The opportunity exists to continue to evolve this distributed observatory to better meet the current needs of heliophysics and the vision for space exploration. The HSO is a central element in the Integrated Research Strategy of the 2013 Decadal Survey and a key element toward answering many of the identified open science questions. The budget must then be preserved in order to insure that this potential is realized.

The Heliophysics budget does not explicitly allow for continuation of the fundamental measurements made by the aging HSO missions. By cooperating with other agencies and by developing low cost flight opportunities (e.g. small-sats, CubeSats and the ISS), it is possible that critical observational input to the HSO can be maintained during these difficult financial times.

The Evolving Heliophysics System Observatory

The HSO will continue to evolve as new spacecraft join and older ones retire or change their operating modes. Missions both in their prime phase and in extended phases provide the variety of observational perspectives needed to study the range of Sun–Earth-heliosphere connections. The continued relevance of this fleet is maintained through a established review process in which each mission is evaluated to maximize the return on Agency investments. This senior review process determines which spacecraft are most necessary to meet the needs of the Heliophysics program as defined by the NASA

Science Mission Directorate (SMD) 2014 Science Plan. The criteria for continuation include relevance to the goals of the HPD; impact of scientific results as measured by publications, awards, and press releases; spacecraft and instrument health; productivity and vitality of the science team (i.e., quality and impact of published research, training of younger scientists and education and public outreach); promise of future impact and productivity (e.g., due to uniqueness of orbit, instrumentation, and solar cycle phase); and broad accessibility and usability of the data.

The challenge embodied in the HSO is the Heliophysics community dependency on continuous measurements and availability of fundamental data products. Our ability to study the coupled system often depends on a connected set of observations. Each observation, when viewed in isolation, may be routine or typical in some sense, but the combination gives singular insights into workings of the system. NASA's role is not to provide operational monitoring services, but to have the capability to connect disparate observations in order to support ongoing and evolving cross-disciplinary science investigations is critical. The outstanding science questions are many, and a continued distributed observing capability is required into the foreseeable future. The need for these connected measurements must be balanced against the need for new missions. New missions are needed, and they are needed in a timely manner. Launches must occur with a reasonable frequency, and new approaches must be used to lengthen the lifetime of newly launched missions. In this way, we can meet the goals, aspirations, and potential of Heliophysics.

SIDEBAR
Recommendation
Continue preparation and launch of the current missions in development. Carefully monitor cost growth to allow for early mitigation.

Flexible Implementation Plan for the STP and LWS Programs
All STP and LWS science targets recommended by the 2013 Decadal Survey have compelling science objectives designed to explore and advance understanding of the fundamental physical processes in space and develop our understanding of the coupled Sun–heliosphere–Earth system. The science targets for the three STP and one LWS missions, as recommended by the 2013 Decadal Survey, are discussed below. The unprecedented fiscal constraints in the foreseeable future require a measured and flexible approach to the implementation of the recommendations in this Decadal Survey.

Before implementing each STP or LWS science target i.e., before releasing an Announcement of Opportunity (AO), NASA HPD and the Heliophysics Community (e.g. via the Heliophysics Subcommittee, the MOWGs, National Academy Committee for Solar and Space Physics, etc.) should consider whether the rationale used by the Decadal Survey to prioritize the ordering remains in effect. A judgment is also needed on the size of the cost cap for each science investigation. Every time the critical science in the investigation can be addressed within a lower cost cap, Heliophysics should take advantage of that opportunity. Viewing the STP and LWS mission lines by the nominal cost cap values of $500M and $1B respectively will force Heliophysics into a highly unfavorable implementation plan.

Ordering Priority: As the highest priority STP science target, the DS recommended the study of outer heliospheric boundaries as demonstrated by the design reference mission IMAP. The priority was based on three main factors: first, that its prime mission coincides with and provides synergistic measurements with the Voyager Interstellar Mission; second, the need for continuity in solar wind and other interplanetary measurements at the Sun–Earth L1 point; third, the significant opportunity for discovery science. Before releasing the STP-5 AO, NASA should re-evaluate these factors. Specifically, the urgency for implementing an IMAP-like mission as the next STP science target may change if there is a significant degradation or scientific change in the status of the operating Voyager spacecraft or a change in the status of solar wind and interplanetary measurements at L1 (for example a change in strategy or an augmentation in L1 measurement capabilities from other agencies, e.g. NOAA). In this case, NASA should consider soliciting proposals that compete for any of the three recommended science targets as the next STP mission or re-prioritize as appropriate.

Scientific Rationale: Before releasing an AO for the STP and LWS science targets, NASA HPD and the Heliophysics Community should also determine whether the objectives of the particular science target under consideration are likely to be partially or fully addressed by alternative program elements, e.g. recently selected Missions of Opportunity, Explorer missions, partnerships with other SMD Divisions, national and international agencies, or industry. If yes, then NASA should appoint a Science and Technology Definition Team (STDT) to re-define and re-prioritize the science objectives of that particular science target or develop plans to implement the next priority science target. Depending on the scope and complexity of the new STDT-defined design reference mission, NASA could implement it either as an Explorer or a re-structured STP or LWS mission, or as a center-led and -managed flagship mission with instruments or instrument suites provided by individual PIs.

The Flight Programs

This roadmap recommends science targets and associated missions that trace the flow of energy, mass, and momentum through regions and across boundaries. Predominantly, the flow and transfer originates in the Sun's interior, crosses interplanetary space, penetrates planetary magnetospheres, and finds a sink in planetary atmospheres and surfaces; or propagates out to the edges of our solar system where it interacts with interstellar space. The funding profile used to develop this Roadmap is significantly smaller than that assumed by the DS. We have taken the baseline mission costs from the DS report. As a result of these two decisions, implementation is delayed in comparison with the DS.

The major portion of the heliophysics budget is assigned to the flight program elements — to the deployment of new Explorer, STP and LWS missions, and as deemed appropriate to extending those missions in the Heliophysics System Observatory. Consistent with the recommendation of the DS, this roadmap endorses the continuation of these programs as currently structured.

The flight program serves the needs of a broad set of customers: the Heliophysics science community, NASA mission operators, the national operational space weather community led by the National Oceanic and Atmospheric Administration (NOAA) and Department of Defense (DOD), other agencies of the U.S. Government affected by space weather; commercial, and other government agencies that operate spacecraft. The HPD should continue its policy of engaging the stakeholder communities to ensure the identification of significant and compelling scientific goals through a variety of venues such as the Heliophysics Subcommittee, the American Geophysical Union, the National Academies of Science and its Space Studies Board, and the Committee for Solar and Space Physics. The NASA HPD provides the programs with their operating budgets, programmatic guidelines, and management of the scientific goals and objectives.

The flight programs follow NASA Policy Directive (NPD) 7120.4 (Program/ Project Management) and NASA Procedural Requirement (NPR) 7120.5 (NASA Space Flight Program and Project Management Requirements) for both program and flight project management. Projects are formulated, approved, and terminated in accordance with these procedures. These procedures are implemented through the processes described in the NASA Headquarters Science Mission Directorate (SMD) Management Handbook. This roadmap is formulated in concurrence with these policies and procedures.

Explorer Flight Program

The Explorer program provides frequent flight opportunities for focused missions that address exploratory or highest priority new scientific questions, and thereby fill critical gaps in our understanding of Heliophysics. The Roadmap endorses the DS recommendation that the Explorer program be given the highest priority, with a recommended augmentation of $70M/year to the Explorer line starting in FY2019.

The Explorer program strives to:

1. Advance scientific knowledge of heliophysics processes and systems;

2. Add scientific data and other knowledge-based products to data archives for all scientists to access;

3. Publish scientific progress and results in peer-reviewed literature to encourage, to the maximum extent possible, the fullest commercial use of the knowledge gained;

4. Implement technologies prepared in related programs; and

5. Announce scientific progress and results in the news media, the public, scholastic curricula, and materials that can be used to inspire and motivate students to pursue careers in science, technology, engineering and mathematics.

By responding rapidly to new concepts and developments in science and forging synergistic relationships with larger-class strategic missions, Explorer missions play a major role in the ability of the HPD to fulfill its science objectives. These investigations target very focused science topics that are either completely exploratory or augment the strategic line missions through cutting-edge science. In combination with the Heliophysics System Observatory, the Explorer missions offer the opportunity to fill critical science gaps in the prescribed program and resolve many of the highest-level open science questions. Highly competitive selections ensure that the most current and best strategic science will be accomplished. A single Principal Investigator (PI) leads the missions. The PI defines modest and focused scientific investigations that can be developed relatively quickly, generally in 24-36 months or less, and executed on-orbit in less than 2–3 years. However, the recent decline in the Explorer program budget is reflected in the lower mission launch cadence and particularly in the lack of Mid-sized Explorer (MIDEX) missions.

Missions of Opportunity are also funded through the Explorer flight program line. This program allows for highly leveraged science instruments to be placed on spacecraft provided by other agencies or other nations. Fundamental science can be achieved at a fraction of the cost of stand-alone missions by hosting payloads through partnering with other agencies, nations, or commercial spaceflight providers. The TWINS and CINDI missions demonstrate the benefits of such collaborations. NASA's primary means of utilizing alternate platforms is via Missions of Opportunity (MOs) and the current Stand Alone Missions of Opportunities Notices (SALMONs). However, the challenge of multi-organization coordination and the short time-line for response to commercial opportunities calls for a regular cadence and an expeditious mission proposal, review, and selection process. The DS committee concluded that a SALMON line needs to evolve in response to both community input and short-term opportunities more rapidly than the cadence of decadal surveys or even that of larger Explorers (MIDEX and SMEX). It needs to be flexible enough to allow proposal topics ranging from instruments on hosted payloads to a University Explorer (UNEX)-class satellite.

Three recommendations to significantly enhance the effectiveness of this mission line are:

1. Accelerate and expand the Heliophysics Explorer program by restoring the option of Mid-size Explorer (MIDEX) missions and allow them to be offered alternately with Small Explorer (SMEX) missions every 2 to 3 years to meet HPD's science objectives. With the proposed budgets a three-year cadence is possible.

2. Support regular selections of Missions of Opportunity to allow the HPD community to respond quickly to announcements and to leverage limited resources with interagency, international, and commercial flight partners. Through relatively modest investments, such Missions of Opportunity can potentially address many of the high priority science challenges facing the HPD community. Utilize all available options for low cost flights: small-sats, CubeSats and the ISS as examples.

3. Seek a solution to the launcher availability issues attendant to the loss of medium class Delta II launch vehicles to establish and maintain the mix of SMEX and MIDEX missions.

SIDEBAR
Recommendation No. 2
Accelerate and expand the Explorer program. Augment the Explorer program by $70M FY12 per year to establish a desired cadence of 24-36 months alternating between SMEX and Mid-Size Explorer (MIDEX) missions and frequently select Missions of Opportunity through partnerships with national and international space agencies.

Explorer Missions Currently in Formulation/Development

Ionospheric Connection (ICON) will probe the extreme variability of Earth's ionosphere with in situ and remote-sensing instruments. ICON will study fluctuations in the ionosphere that interfere with signals from communications and global positioning satellites, causing reduced or denial of service, and subsequently can have an economic impact on the nation.

Global-scale Observations of the Limb and Disk (GOLD) is an imaging instrument that will fly on a commercial communications satellite in geostationary orbit to image the Earth's thermosphere and ionosphere to examine the response of the Earth's upper atmosphere to forcing from the Sun and the lower atmosphere.

Solar Terrestrial Probes Flight Program
The STP missions target unsolved scientific questions that are critical for understanding the fundamental physical processes that determine the mass, momentum, and energy flow in the solar system from the Sun to planetary bodies including Earth and to the interstellar boundary and its interaction with the local interstellar medium. STP missions study this system for insight concerning how it evolved and what will happen in the future. Successive missions focus on critical science targets that systematically advance understanding of the coupled solar-heliosphere-terrestrial system. These missions use an innovative blend of in situ and remote sensing observations, often from multiple platforms. STP program objectives are:

1. To describe the system behavior of the magnetic variable star, our Sun, and its interaction with the entire solar system;
2. To understand the critical physics that link the Sun, Earth, heliosphere, and the interstellar medium; and,
3. To understand the processes and dynamics of the magnetosphere-ionosphere-upper atmosphere system, the near space electromagnetic plasma environment surrounding the Earth.

Specific Recommendations for re-structuring the STP program are:
- Execute STP missions through a funding line with a stable budget.
- Cost-cap each mission with a specified ceiling on full lifecycle costs as described in

Chapter 3. The DS applied a cost cap of ~$500M FY12 for the science investigations described below. This Roadmap carries that funding level in budget projections and recommends that the HPD and future Roadmaps revisit these assumptions. Future Roadmaps and the HPD should examine the possibility of trading cost-cap for launch frequency in the strategic mission programs.

- Implement STP missions as PI-led missions, with the PI fully empowered and motivated to make the scientific and mission trade-offs necessary to remain within the cost cap.
- Missions must be confirmed with adequate reserves to remain within the cost cap, and should have de-scope options in case the cost cap is breached. In the event that there is cost growth beyond the control of the PI, these impacts need to be absorbed within the STP funding line, with no additional liens on other program elements in the HPD.
- Select missions competitively, restricting each selection to a specific science goal in order to achieve the prioritized scientific and strategic objectives described below (also see Flexible Implementation Plan for the Re-structured STP and LWS programs described above).

Recommendation No. 3
Restructure Solar Terrestrial Probes as a moderate-scale, competed, principal-investigator-led (PI-led) mission line that is cost-capped at ~$500 million (or less) per mission in fiscal year 2012 dollars including full life-cycle costs.

Missions Currently in Formulation/Development

Magnetospheric Multiscale (MMS) Mission
Understand the microphysics of magnetic reconnection.
The MMS mission is currently in development and will use Earth's magnetosphere as a laboratory to study the microphysics of magnetic reconnection, a fundamental plasma-physical process that converts magnetic energy into heat and the kinetic energy of charged particles. In addition to seeking to solve the mystery of the small-scale physics of the reconnection process, MMS will also investigate how the energy conversion that occurs in magnetic reconnection accelerates particles to high energies and what role plasma turbulence plays in reconnection events. These processes—magnetic reconnection, particle acceleration, and turbulence—occur in all astrophysical plasma systems but can be studied in situ only in our solar system and most efficiently in Earth's magnetosphere, where they control the dynamics of the geospace environment and play an important role in the phenomena known as "space weather." The MMS mission comprises four identically instrumented spacecraft that measure particles, fields, and plasmas.

Recommended New Science Targets for the STP Program

A detailed description of these targets is found in Chapter 5. The restructured STP program involves moderate-size missions being competitively selected, with science targets that systematically advance understanding of the fully- coupled solar-heliosphere-terrestrial system. The nominal science targets for the STP line, as recommended by the 2013 Decadal Survey, are shown below. As described above, this Roadmap recommends that the HPD and future Roadmaps reexamine these priorities and the recommended STP flight sequence depending upon whether and how the associated science objectives might be addressed by other program elements. With a nominal AO for STP#5 in FY17, there is time for the community to assess the science case for each STP mission recommended by the DS, and the fiscal situation faced by the HPD.

Heliospheric Boundary and Solar Wind Plasma Mission

Understand the nature of the interstellar boundary and its interaction with the interstellar medium and unravel the mechanisms by which particles are energized throughout the heliosphere

One new STP science target is to understand the outer heliosphere and its interaction with the interstellar medium, as illustrated by the DS design reference mission Interstellar Mapping and Acceleration Probe (IMAP). The mission implementation also advances understanding of the acceleration of energetic particles and requires measurements of interplanetary disturbances and solar wind that impact the terrestrial system and the heliosphere.

The last decade has seen breakthroughs in the knowledge of the outer boundaries of the heliosphere and their interactions with the local galactic neighborhood. These advances include the crossing of the termination shock by the Voyager spacecraft, the IBEX images of enhanced energetic neutral atom emission from a localized "ribbon" that encircles the heliosphere, and the inference of the absence of a bow shock beyond the heliopause. The scientific motivation for a more advanced mission to measure the key components of the interstellar gas, globally image the fine-scale spatial and temporal properties of the heliospheric boundaries and understand how they interact with the interstellar medium is not only compelling but also pressing since the Voyager spacecraft will only operate through this decade.

Lower Atmosphere Driving Mission

Understand how lower atmospheric wave energy drives the variability and structure of the near-Earth plasma.

A second STP science target is to provide a comprehensive understanding of the variability in space weather driven by lower-atmospheric weather on Earth. This target is illustrated by the DS design reference mission Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC).

The lower atmosphere driving mission is designed to answer the question: "How does lower atmosphere variability affect geospace?" To understand how lower-atmosphere variability drives neutral and plasma variability in the IT system, a mission must address wave coupling with the lower atmosphere. The representative mission is designed to do two things. First, it will reveal the fundamental processes (e.g., wave dissipation, interactions between flow of different species) that underlie the transfer of energy and momentum into the IT system (especially within the critical 100-200 km height regime). Second, it will measure the resultant thermospheric and ionospheric variability that these waves incur at higher altitudes. It will do these on a global scale, with high-inclination satellites launched into orbits separated by 6 hours of local time, providing the coverage necessary to resolve critical atmospheric tidal components and the effects of wave-wave interaction.

Magnetosphere Ionosphere Thermosphere Coupling Mission
Understand the interconnected multi-scale behavior of the magnetosphere-ionosphere system

A third STP science target is to determine how the magnetosphere-ionosphere-thermosphere system is coupled and how it responds to solar and magnetospheric forcing. This target is illustrated by the DS design reference mission Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI; Chapter 5).

The magnetosphere-ionosphere-thermosphere coupling mission is aimed at determining how the complex magnetosphere-ionosphere-thermosphere (MIT) system is coupled and responds to external solar and internal magnetospheric forcing. Regions of geospace are intrinsically interconnected over diverse scales of space and time. Plasma and fields in the ionosphere and magnetosphere interact, and multiple processes compete simultaneously. Observation of the relationships among components is critical to understand and characterize collective behavior of this complex system across a broad range of spatial scales.

Living With a Star Flight Program
The LWS program emphasizes the science necessary to understand those aspects of the Sun and the Earth's space environment that affect life and society. The ultimate goal is to provide a predictive understanding of the system, and specifically of the space weather conditions at Earth and the interplanetary medium.

LWS missions are formulated to answer the specific questions needed to understand the linkages among the interconnected systems that impact us. LWS science products impact the technologies associated with space systems, communications and navigation, and ground systems such as power grids. LWS products also improve understanding of the ionizing radiation environment, which has applicability to human radiation exposure in the International Space Station, to high-altitude aircraft flight, and to future space exploration with and without human presence. The science products impact life and society by improving the definition of solar radiation that is a forcing function for global climate change, surface warming, and ozone depletion and recovery. The LWS program objectives are based upon these goals and are as follows:

1. Understand solar variability and its effects on the space and Earth environments with an ultimate goal of a reliable predictive capability of solar variability and response.

2. Obtain scientific knowledge relevant to mitigation or accommodation of undesirable effects of solar variability on humans and human technology on the ground and in space.

3. Understand how solar variability affects hardware performance and operations in space.

Missions Currently in Formulation/Development

Solar Orbiter Collaboration (SOC)

Understand the inner heliosphere and the unexplored near-Sun polar regions of the Sun. ESA's Solar Orbiter mission will orbit within one-fifth of Earth's distance from the Sun to perform a close-up study of our Sun and inner heliosphere. At these distances, the spacecraft will be closer to the Sun than any previous mission and for short periods will almost co-rotate with the surface of the Sun. The goals of this mission are to determine in situ the properties and dynamics of plasma, fields, and particles in the near-Sun heliosphere; to survey the fine detail of the Sun's magnetized atmosphere; to identify the links between activity on the Sun's surface and the resulting evolution of the corona and inner heliosphere; and to characterize the Sun's polar regions and equatorial corona from high latitudes.

Solar Probe Plus (SPP)

The Solar Probe Plus will be a historic mission, flying into the Sun's atmosphere (or corona), for the first time. Solar Probe Plus will approach as close as nine solar radii from the surface of the Sun, repeatedly sampling the near-Sun environment. By directly probing the solar corona, this mission will revolutionize our knowledge and understanding of coronal heating and of the origin and acceleration of the solar wind, critical questions in heliophysics that have been ranked as top priorities for decades. Two of the transformative advances in our understanding of the Sun and its influence on the solar system were the discovery that the corona is hundreds to thousands of times hotter than the visible solar surface (the photosphere) and the development—and observational confirmation—of the theory of the corona's supersonic expansion into interplanetary space as the solar wind. By making the first direct, in situ measurements of the region where some of the most hazardous solar energetic particles are energized, Solar Probe Plus will make a fundamental contribution to our ability to characterize and forecast the extended radiation environment in which future space explorers will work and live.

Supporting Flight Elements

Space Environment Testbeds (SET)

The SET project will fly as a piggyback payload on the U.S. Air Force Deployable Structures Experiment (DSX) mission, which is scheduled for launch no earlier than 2016. This will perform flight and ground investigations to characterize the space environment and its impact on hardware performance in space.

Recommended New Science Targets for the LWS Program

A detailed description of these targets is found in Chapter 5.

Recommendation No. 4 *Implement a Living With a Star mission to study the ionosphere-thermosphere-mesosphere system in an integrated fashion. Following the launch of the Solar Orbiter Collaboration and Solar Probe Plus, the next LWS science target should focus on how Earth's atmosphere absorbs solar wind energy.*

Geospace Dynamics Coupling Mission (GDC)

Understand how the ionosphere-magnetosphere system responds to and regulates magnetospheric forcing over local and global scales.

This target is illustrated by the DS design reference mission Geospace Dynamics Constellation mission (GDC; Chp 5). During geomagnetic storms, solar wind energy is deposited in Earth's atmosphere, but only after being transformed and directed by a number of processes in geospace. The primary focus of the geospace dynamics constellation reference mission is to reveal how the atmosphere, ionosphere and magnetosphere are coupled together as a system and to understand how this system regulates the response of all geospace to external energy input. Using current and foreseeable technologies, the reference mission uses a systematic and robust observational approach to measure all the critical parameters of the system in optimally spaced orbital planes, thus providing unprecedented coverage in both local time and latitude. Moreover, spacecraft in the constellation will orbit at relatively low altitudes where both neutral and ionized gases are strongly coupled through dynamical and chemical processes. This brings a new focus to critical scientific questions:

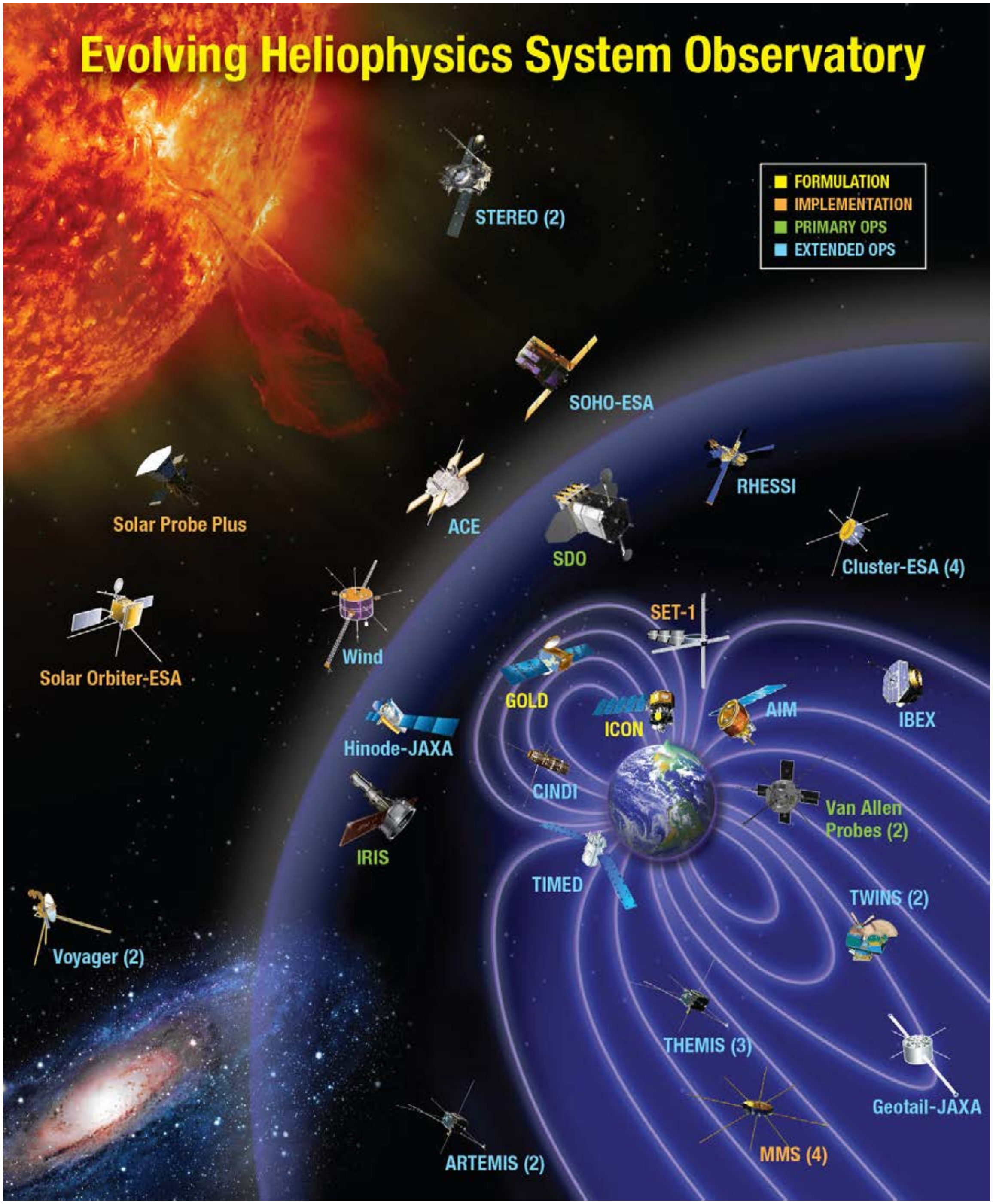
1. How do solar wind/magnetospheric energy energize the ionosphere and thermosphere (I-T)?
2. How does the I-T system respond and ultimately modify how the magnetosphere transmits solar wind energy to Earth?
3. How is solar-wind energy partitioned into dynamical and chemical effects in the I-T system, and what temporal and spatial scales of interaction determine this partitioning?
4. How are these effects modified by the dynamical and energetic variability of the ionosphere- upper atmosphere introduced by atmospheric wave forcing from below?

Heliophysics missions currently operating are shown in Table XX. Each mission is listed within the Heliophysics program element from which they are funded. Heliophysics currently has 18 operating missions (using 29 spacecraft): Voyager, Geotail, Wind, SOHO, ACE, Cluster, TIMED, RHESSI, TWINS, Hinode, STEREO, THEMIS/ARTEMIS, AIM, CINDI, IBEX, SDO, Van Allen Probes, and IRIS.

Mission—Launch Year (Extended or Prime), Partners	**Objective**
Solar Terrestrial Probes Program	
Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics (TIMED)—2001 (Extended)	Explores the Earth's Mesosphere and Lower Thermosphere (60–180 kilometers above the surface), to understand the transfer of energy into and out of these regions and the basic structure that results from the energy transfer into the region.
Hinode (Solar B)—2006 (Extended) in partnership with Japan and the United Kingdom	Studies the generation, transport, and dissipation of magnetic energy from the photosphere to the corona to record how energy stored in the Sun's magnetic field is released, either gradually or violently, as the field rises into the Sun's atmosphere.

Mission—Launch Year (Extended or Prime), Partners	Objective
Solar Terrestrial Relations Observatory (STEREO)—2006 (Extended) in partnership with France, Switzerland, United Kingdom, Germany, Belgium, DOD	Traces the flow of energy and matter from the Sun to Earth with two space-based observatories. Reveals the 3D structure of coronal mass ejections and tracks their propagation through space.. STEREO observations are used for space weather forecasting by NOAA.
Living With a Star Program	
Solar Dynamics Observatory (SDO)—2010 (Prime)	Studies the origins of solar activity and the Sun's dynamic behavior by measuring the Sun's interior, magnetic field, the hot plasma of the solar corona, and solar spectral irradiance.
Van Allen Probes (formerly, Radiation Belt Storm Probes)—2012 (Extended) in partnership with Czech Republic	Uses twin spacecraft in elliptical orbits to provide an understanding, ideally to the point of predictability, of how populations of relativistic electrons and penetrating ions in space form or change in response to variable inputs of energy from the Sun.
Heliophysics Explorer Program	
Advanced Composition Explorer (ACE)—1997 (Extended)	Observes particles of solar, interplanetary, interstellar and galactic origins. Solar wind observations are used on an operational basis for space weather forecasting by both NOAA and USAF.
Reuven Ramaty High Energy Solar Spectroscope Imager (RHESSI)—2002 (Extended)	Advances our understanding of the fundamental high-energy processes at the core of solar flares by imaging them in X-rays and Gamma rays by obtaining a detailed energy spectrum at each point of the image.
Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS)—2006 and 2008 (Extended) in partnership with NRO, Germany	Enables the 3-D visualization and the resolution of large scale structures and dynamics within the magnetosphere by imaging the charge exchange of neutral atoms over a broad energy range, using two identical instruments on two widely spaced high-altitude, high-inclination spacecraft
Time History of Events and Macroscale Interactions during Substorms (THEMIS)—2007 (Extended) in partnership with Germany, France, and Austria	Originally used five identically instrumented spacecraft to study the nature of sub-storm instabilities that abruptly and explosively release solar wind energy stored within Earth's magnetotail. Two of the five spacecraft were repurposed and renamed ARTEMIS, they currently study the space environment around the Moon.
Aeronomy of Ice in the Mesosphere (AIM)—2007 (Extended)	Explores Polar Mesospheric Clouds, which form an icy membrane at the edge of Earth's atmosphere, to find out why they form and why they are changing.
Coupled Ion-Neutral Dynamics Investigation (CINDI)—2008 (Extended) in partnership with USAF	Uncovers the role of ion-neutral interactions in the generation of small and large-scale electric fields in the Earth's upper atmosphere.
Interstellar Boundary Explorer (IBEX)—2008 (Extended) in partnership with Switzerland	Measures energetic neutral atoms created at the boundary that separates our heliosphere from the local interstellar medium, giving us the first evolving images of the heliosphere's outer edge and surroundings.
Interface Region Imaging Spectrograph (IRIS)—2013 (Prime) in partnership with Norway	Increases our understanding of how the Sun's interface region powers its corona and the energy flow into the corona and solar wind. It also provides an archetype for all stellar atmospheres by tracing the flow of energy and plasma through the chromosphere and transition region into the corona using spectroscopy and imaging.

Mission—Launch Year (Extended or Prime), Partners	Objective
Heliophysics Research Program	
Cluster-II—2000 (Extended) in partnership with ESA	The four identical Cluster II satellites study the impact of the Sun's activity on the Earth's space environment by flying in formation around Earth. The mission collects three-dimensional data of solar wind interactions with the magnetosphere and the near-Earth space environment.
Geotail—1992 (Extended) in partnership with Japan	Studies the dynamics of the Earth's magnetotail over a wide range of distances and measures global energy flow and transformation in the magnetotail.
Solar and Heliospheric Observatory (SOHO)—1995 (Extended) in partnership with ESA	Studies the internal structure of the Sun, its extensive outer atmosphere and the origin of the solar wind and solar energetic particles. SOHO observations are used for space weather forecasting by NOAA and have been used by citizen scientists to discover more than 2,700 comets.
Voyager—1977 (Extended)	The Voyager Interstellar Mission explores the outer heliosphere, heliosheath and the interstellar medium with plasma, energetic particle, magnetic field and plasma wave instrumentation. The two Voyagers hold the records of the longest-operating and the most distant spacecraft.
Wind—1994 (Extended) in partnership with France	Measures solar radio bursts, solar wind and energetic particle properties, and complements ACE measurements from near the Lagrange 1 (L1) point. It also supports investigations of Gamma ray bursts in tandem with the Astrophysics SWIFT Gamma-ray Explorer mission.


Evolving Heliophysics System Observatory
FORMULATION
IMPLEMENTATION
PRIMARY OPS
EXTENDED OPS
STEREO (2)
SOHO-ESA
RHESSI
Solar Probe Plus
ACE
SDO
Cluster-ESA (4)
SET-1
Wind
Solar Orbiter-ESA
GOLD
AIM
IBEX
ICON
Hinode-JAXA
CINDI
Van Allen
Probes (2)
IRIS
TIMED
TWINS (2)
Voyager (2)
THEMIS (3)
Geotail-JAXA
MMS (4)
ARTEMIS (2)

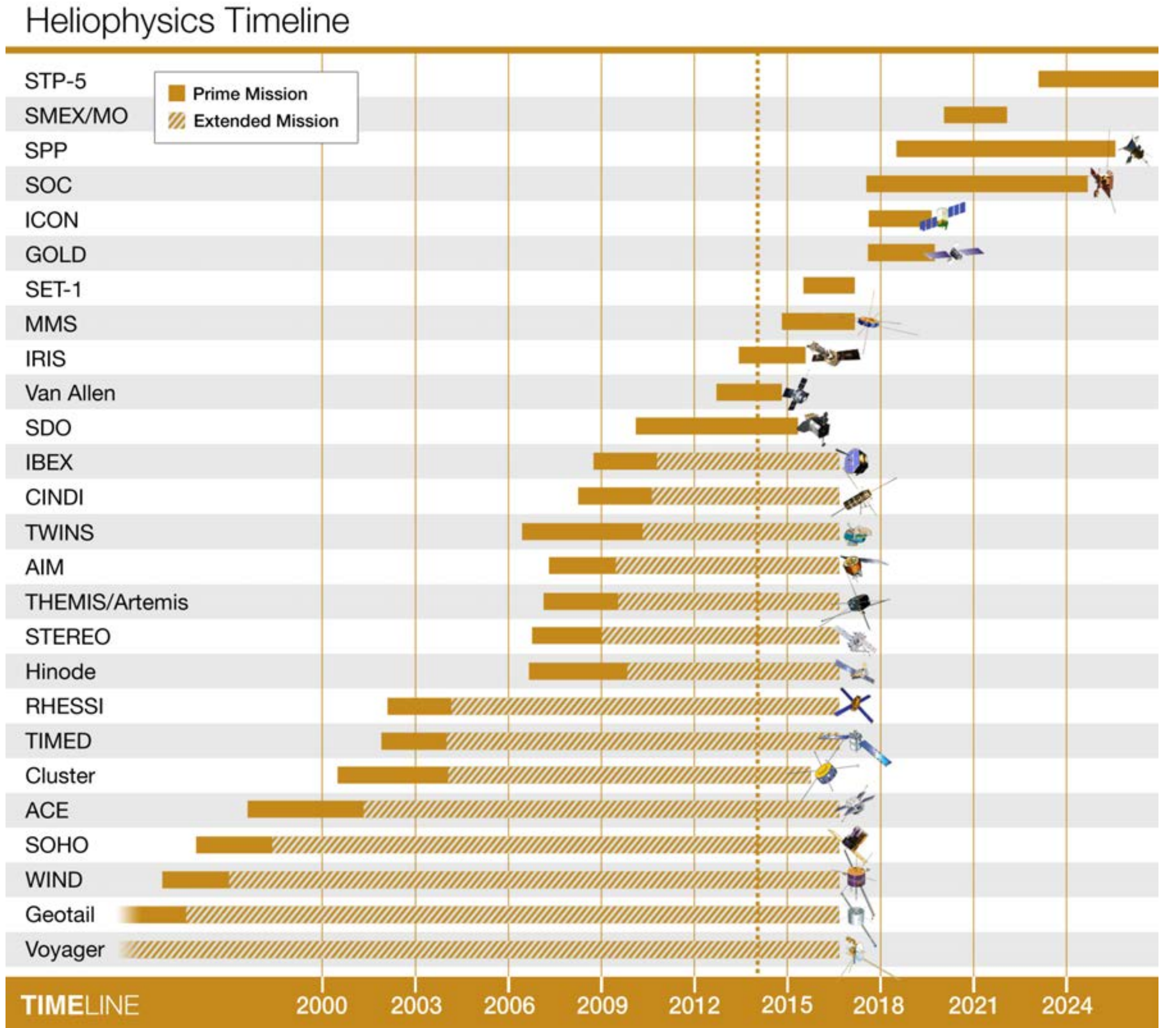


Table 4.1c Heliophysics Future Missions

Mission—Expected Launch Year, Partners	Objective
Solar Terrestrial Probes Program	
Heliospheric Boundary and Solar Wind Plasma Mission - 2022	Advance our understanding of the interstellar boundary and its interaction with the interstellar medium through remote sensing observation and unravel the mechanisms by which particles are energized.
Lower Atmosphere Driving Mission - 2025	Understand how lower atmospheric wave energy drives the variability and structure of the near-Earth plasma.
Magnetosphere-Ionosphere-Thermosphere Coupling Mission – 2033	Determine how the magnetosphere-ionosphere-thermosphere system is coupled and responds to solar and magnetospheric forcing.

Living With a Star Program	
Geospace Dynamics Coupling Mission—2030	To characterize and understand the coupled magnetosphere-ionosphere-atmosphere system as a regulator of the response of geospace to external energy inputs.
Heliophysics Explorer Program	
Explorers and Missions of Opportunity – 2021, 2024, 2026, 2029	High priority science investigations, filling focused, critical gaps in our knowledge

Science Targets for the Explorer, STP, LWS and supporting flight programs: 2023-2033
Other high priority science investigations and targets for Explorer, STP and/or LWS programs could include (*Note that this is not a prioritized or complete list, the targets are taken from the DS panel reports. See Appendix G for a list of community contributed science investigation quadcharts)*:

ESCAPE: Energetics, Sources and Couplings of Atmosphere-Plasma Mission
The primary goal of the ESCAPE mission is to answer the question: How are ionospheric outflows energized? A key aspect of the mission, relevant to space weather prediction, is to determine how the outflow flux and other properties such as composition, density and energy vary with electromagnetic and precipitating particle energy inputs into the outflow source region, e.g., the efficiency of energy conversion may be quantitatively expressed as an intensive transport relation between EM energy flux and particle energy flux. Such relations are crucial elements of simulation models of atmosphere-ionosphere-magnetosphere (AIM) dynamics, yet little reliable information is available on their form.

The Interstellar Probe Mission
The Interstellar Probe would make comprehensive, state-of-the-art, in-situ measurements of plasma and energetic-particle composition, magnetic fields, plasma waves, ionic charge states, energetic neutrals, and dust that are required for understanding the nature of the outer heliosphere and exploring our local galactic environment. Advanced scientific instrumentation for an Interstellar Probe does not require new technology. The main technical hurdle is propulsion. Also required are electric power from a low-specific-mass radioactive power source and reliable, sensitive, deep-space, high throughput communications.

MAC: Magnetosphere Atmosphere Coupling Mission
The ability to specify the energy input and view the dynamic state of a large volume at middle and high latitudes over time periods ranging from less than one minute to many tens of minutes is necessary to determine how magnetosphere-atmosphere coupling processes affect the behavior of both regions. This challenge can be efficiently met with a Magnetosphere-Atmosphere Coupling mission (MAC). With two spacecraft spaced in the same orbit in the ionosphere and a single satellite imaging the sampled volume from high altitude it is possible to identify coherent spatial features in the input drivers from the magnetosphere and the temporal and spatial scales over which the ionosphere and thermosphere respond.

Magnetosphere Constellation and Tomography (MagCaT)

The MagCat mission addresses some of the most critical processes in Sun-Earth connections: plasma entry into the magnetosphere, plasma-sheet formation and dynamics, and investigation of bow-shock structure, plasmaspheric plumes, and other mesoscale structures that form in response to solar wind variability. To achieve this objective requires observations with a minimum spatial resolution of 0.5 Re at a minimum time cadence of 15s. MagCat could provide those required measurements. MagCat is a 20-spacecraft mission that would provide a combination of two-dimensional images of the equatorial magnetosphere and multi-point in situ observations made concurrently from within the same imaged region.

Magnetospheric Constellation (MagCon)
The prime overarching objective of the mission is to understand the mass and energy transport at global and mesoscales in Earth's magnetosphere and to determine how the magnetosphere stores, processes, and releases energy in the magnetotail and accelerates particles that supply Earth's radiation belts. A multi-satellite in situ mission such as MagCon is required to track the spatial-temporal plasma structures and flows associated with the solar wind plasma entry across the magnetopause and transport within and through the magnetotail. Throughout the mission, MagCon would provide a global "picture" of these otherwise invisible regions of the magnetosphere.

Magnetosphere-Ionosphere Source Term Energetics (MISTE)
Magnetosphere-Ionosphere Source Term Energetics (MISTE) mission is designed to resolve how ionospheric plasma escapes into the magnetosphere, and quantify the amount of outflow as functions of electromagnetic and particle energy input into the upper atmosphere. Outflowing ions represent an important source of plasma for the magnetosphere. The MISTE concept calls for two identical spacecraft in highly inclined, elliptical orbits with apogees 180° out of phase and is designed to simultaneously measure the inflow of energy to the upper atmosphere and the outflow of ions back to the magnetosphere.

Solar-C
Solar-C is designed to study the magnetized solar atmosphere at unprecedented spatial, temporal and spectral resolution. The fundamental plasma processes related to reconnection, wave generation and ion-neutral interactions would be the focus of the mission. US participation in a future Solar-C mission was the highest ranked solar opportunity by the Decadal Survey's Solar and Heliospheric Physics Panel. As an international partnership mission, the cost to NASA is well below that of the strategic missions. However, the science return from Solar-C would be comparable to a strategic mission.

The Solar Eruptive Events (SEE) Mission
Major solar eruptive events (SEEs), each consisting of a large flare and an associated fast CME, are the most powerful explosions and particle accelerators in the solar system. Understanding the fundamental physics of such events is one of the most important goals of heliophysics, not only because of the critical space weather concerns, but also because they provide the most accessible laboratory for investigating the poorly understood

processes of energy release and efficient particle acceleration in magnetized plasmas throughout the universe. The SEE mission utilizes a single 3-axes stabilized, Sun-pointed spacecraft in low Earth orbit and will address these science questions by measuring the energetically and diagnostically important aspects of solar eruptive events.

The Solar Polar Imager Mission
Our current understanding of the Sun, its atmosphere, and the heliosphere is severely limited by a lack of observations of the Sun's polar regions. The Solar Polar Imager (SPI) mission concept would go into a 0.48-AU circular orbit with 60° inclination to conduct extended observations of solar polar regions, enabling the determination of polar flows down to the tachocline, where the solar dynamo is thought to originate. The rapid 4-month orbit, combined with in situ and remote-sensing instrumentation, will enable unprecedented studies of the physical connections between the Sun, the solar wind, and SEPs. Solar-sail propulsion is proposed to place SPI into its orbit.

The Sun-Earth L_5 Lagrangian Point Mission
The L_5 mission concept would place a spacecraft carrying imaging and in-situ instruments in an orbit about the L_5 Lagrangian point, located 1 AU from the Sun and Earth. From that location, the mission could make major advances in helioseismology by probing for variations in the deep sub-surface structure and dynamics associated with the solar dynamo, observe emerging active regions before they affect Earth, study CME evolution and interaction with the solar wind in propagation from Sun to Earth, and make major advances in space-weather forecasting. The spacecraft would reside in this region, rather than travel through it as the STEREO mission did.

Supporting Research Activities

The DRIVE Initiative

The highest priority new recommendation of the 2013 NRC Decadal Survey for Heliophysics is the DRIVE initiative (Diversify, Realize, Integrate, Venture, Educate) that represents an integrated approach to the management of crucial infrastructure investments and supporting program elements for spaceflight missions. The DRIVE initiative recognizes that the HPD cultivates a wide range of supporting programs, including basic research and modeling, mission operations and data analysis, suborbital programs, and instrument development. These vital supporting program elements provide the scientific foundation for the Heliophysics missions. Below, the main elements proposed by the DS DRIVE initiative are outlined before the elements of the Heliophysics research program are described.

The Roadmap Team fully supports the DRIVE initiative and its intent to develop more fully and implement more effectively the many experimental and theoretical assets at NASA, NSF, and other agencies. DRIVE champions relatively low-cost activities that maximize the scientific return of ongoing projects and enables new projects, with the goal of achieving an optimal balance of spaceflight missions of various sizes with supporting programs and infrastructure investments that will be necessary for a successful Heliophysics scientific program.

Significant progress in Heliophysics requires the development of a deep understanding of multiple connected physical systems. In this regard, DRIVE complements and utilizes the HSO in order to cultivate a "system science" approach to heliophysics research, and seeks to develop and nurture a cadre of researchers who can cross discipline boundaries seamlessly to develop theoretical and computational models that extract the essential physics from measurements made across multiple observing platforms. DRIVE is an initiative unified not by a central management structure, but through a comprehensive set of multi-agency recommendations that will facilitate scientific discovery. The specific elements of the proposed DRIVE initiative implementation for NASA are:

- Diversify observing platforms with microsatellites and mid-scale ground-based assets.
- Realize scientific potential by sufficiently funding operations and data analysis.
- Integrate observing platforms and strengthen ties between agency disciplines.
- Venture forward with science centers and instrument and technology development.
- Educate, empower, and inspire the next generation of space researchers

The Roadmap Team commends HPD efforts to implement the DRIVE-related recommendations of the 2013 Decadal Survey. In particular, Table XX shows how the different elements of the Heliophysics Research program were reorganized in the 2014 Research Opportunities in Space and Earth Sciences (ROSES) Solicitation announcement and how they align with the five components of the DRIVE initiative. The outyear funding increments for each element are also included. The remainder of this section describes the DRIVE and ROSES elements in more detail.

Table XX: Relationship between DRIVE components and the 2014 ROSES elements. $40M/yr added to the research program, fully funded by FY19

Component	Decadal Survey Recommendation	2014 ROSES Element

Diversify observing platforms with microsatellites and mid-scale ground-based assets	A NASA tiny-satellite grants program should be implemented, augmenting the current Low-Cost Access to Space (LCAS) program, to enable a broadened set of observations, technology development, and student training. Sounding rocket, balloon, and tiny-satellite experiments should be managed and funded at a level to enable a combined new-start rate of at least six per year, requiring the addition of $9 million per year (plus an increase for inflation) to the current LCAS new-start budget of $4 million per year for all of solar and space physics.	Heliophysics Technology and Instrument Development for Science (H-TIDEeS) Heliophysics Living With a Star Science
Realize scientific potential by sufficiently funding operations and data analysis	NASA should permanently augment OM&DA support within the program lines by $10 million per year plus annual increases for inflation, in order to take advantage of new opportunities yielded by the increasingly rich Heliophysics Systems Observatory assets and data. A directed guest investigator program, set at a percentage (≈ 2 percent) of the total future NASA mission cost, should be established in order to maximize scientific return. Further, just as an instrument de-scoping would require an evaluation of impact on mission science goals, so, too, should the consequences of a reduction in mission-specific GI programs and Phase-E funding merit an equally stringent evaluation.	Heliophysics Supporting Research (H-SR) Heliophysics Living With a Star Targeted Research & Technology (H-LWS TR&T) Heliophysics Mission Operations and Data Analysis Heliophysics Guest Investigators (H-GI)
Integrate observing platforms and strengthen ties between	NASA should join with NSF and DOE in a multi-agency program on laboratory plasma astrophysics and spectroscopy, with an expected NASA contribution ramping from	Heliophysics Technology and Instrument Development for Science (H-

agency disciplines	$2 million per year (plus increases for inflation), in order to obtain unique insights into fundamental physical processes. NASA, NSF, and other agencies should coordinate ground- and space-based solar-terrestrial observational and technology programs and expand efforts to take advantage of the synergy gained by multiscale observations.	TIDEeS) Heliophysics Infrastructure and Data Environment Enhancements (H-IDEE)
<u>Venture</u> forward with science centers and instrument and technology development	NASA and NSF together should create heliophysics science centers (HSCs) to tackle the key science problems of solar and space physics that require multidisciplinary teams of theorists, observers, modelers, and computer scientists, with annual funding in the range of $1 million to $3 million for each center for 6 years, requiring NASA funds ramping to $8 million per year (plus increases for inflation). NASA should consolidate technology funding now in SR&T, LWS, and LCAS into a single Heliophysics Instrument and Technology Development Program (HITDP) and increase current annual funding levels, ramping to $4 million per year (plus increases for inflation) in order to facilitate urgently needed innovations required for future heliophysics mission implementation. Further, issues pertaining to constellation mission implementation (e.g., communications, operations, propulsion, and launch mechanisms) should be explicitly addressed.	Heliophysics – Grand Challenges Research (H-GCR) Heliophysics Living With a Star Science Heliophysics Technology and Instrument Development for Science (H-TIDEeS)
<u>Educate,</u> empower, and inspire the next generation of		See Roadmap Chapter 7

space researchers		

The *Diversify* component aims to fully exploit the dawn of the era of opportunities for multipoint and multiscale measurements for the exploration of the complex heliospheric system with an increasingly diverse set of platforms and technologies. Specifically, it calls for the strategic use of diverse assets that range from large missions and facilities, through Explorers and mid-sized projects, down to small CubeSats, and suborbital rocket and balloon flights. Only by employing a balanced mixture of observing techniques can we hope to fully exploit new opportunities that arise as our scientific insight evolves. The utilization of the appropriate approach for each targeted measurement is the key to a thorough, but cost-effective, observing program. Suborbital science missions in Heliophysics are supported by the Low Cost Access to Space (LCAS) program, which also provides a unique avenue for graduate-student training and technology development. To enable a broadened set of observations, technology development, and student training, the DRIVE initiative calls for an increase in the present cadence of sounding rocket and balloon investigations, and the introduction of a tiny satellites program within the LCAS program to address exciting new avenues for scientific investigation. The recommendation is that sounding rocket, balloon, and tiny-satellite experiments should be managed and funded at a level to enable a combined new-start rate of at least six per year, requiring the addition of $9 million per year to the current LCAS new-start budget of $4 million per year for all of solar and space physics.

The *Realize* component aims to fulfill the scientific potential of Heliophysics assets by providing strategic investment to ensure that the right measurements are performed over each mission's lifetime and that the new data are analyzed fully. Essential to this goal is funding for a focused data analysis program that supports science goals that may span platforms or change throughout a mission. The Decadal Survey committee concluded that a higher level of Mission Operations and Data Analysis (MO&DA) funding is required to exploit the opportunities created by the HSO, especially considering the importance of broad and extended data sets for exploring connected system science for space weather events and space climatology. To expand the potential for new discoveries from data, it is essential to maintain a stable general guest-investigator program, a primary funding source for research utilizing data from missions beyond their prime mission phase. The recommendation for NASA is a permanent augmentation of MO&DA support by $10 million per year in order to take advantage of new opportunities yielded by the increasingly rich HSO assets and data. In addition, broadening participation in and facilitating new discoveries through a NASA mission-specific guest investigator program bolster mission success. To maximize scientific return, this directed guest investigator program, set at a percentage (approximately 2 percent) of the total future NASA mission cost, should be established, with any proposed reduction in this program subject to a stringent evaluation of the impact on mission science goals.

The *Integrate* component addresses directly the particular challenges faced by heliophysics research, an inherently multidisciplinary science, in terms of both the range of topics within its subfields and in its interfaces with physics, chemistry, astronomy, and planetary and Earth science. A "system science" approach fosters the potential for breakthrough science at the interfaces of these disciplines. At modest cost, the combination of diverse space- and ground-based assets maximizes their multiscale potential for understanding the heliophysical system as a whole, as recently demonstrated by the Whole Heliospheric Interval campaign in 2008. Furthermore, the development of connections between heliophysics and these related scientific disciplines strengthen insight into shared, fundamental physical processes. The Decadal Survey committee recommended several implementations at NASA to meet these goals, including support for dedicated laboratory experiments, the strengthening of ties between relevant NASA divisions, and further efforts to coordinate observational data from diverse instruments. Experimental studies in the laboratory are a vital complement to modeling and observation in heliophysics, probing fundamental plasma physical processes and producing chemical and spectroscopic measurements that support satellite measurements and atmospheric models; and the HPD has historically supported such projects through existing funding programs. The Decadal Survey report recommended that NASA should join with NSF and DOE to establish a formal multi-agency program on laboratory plasma astrophysics and spectroscopy, with an expected NASA contribution ramping from $2 million per year in order to obtain unique insights into fundamental physical processes. In addition, multidisciplinary collaborations between NASA's HPD and the Astrophysics, Planetary Sciences, and Earth Sciences Divisions should be encouraged for the potential of mutual benefit. Finally, coordinated investigations synthesizing data from diverse space- and ground-based instruments are likely to be a crucial element of future breakthrough science and to provide new pathways for translating scientific knowledge into societal value. It is recommended that NASA should expand efforts to coordinate with NSF and other agencies to take advantage of the synergy gained by such multiscale observations.

The *Venture* component transforms the approach to tackling grand challenge science problems and new instrument and technology development. Major advances in heliophysics research require innovation in both theory and technology, so cultivating healthy programs in each is vital to the field of heliophysics. Major advances in the grand challenge problems at the frontier of heliophysics research require close interaction between observers, theorists, and modelers to stimulate new ideas to explore with analytic theory, influence the interpretation of observations, and motivate the need for new missions. Yet limitations of funding in support of research and analysis over the last decade have resulted in increasingly fragmented science, where individual researchers must rely on multiple proposals to secure adequate funding. The Decadal Survey committee recommended the establishment of a Heliophysics Science Center (HSC) program to bring together critically sized teams of observers, theorists, modelers, and computer scientists to address the most challenging problems in solar and space physics. The centers should be designed to highlight the exciting science problems of the field to bolster the interest of faculty at universities and to attract top students to the field. NASA and NSF together should create Heliophysics Science Centers, with annual funding in the range of $1 million to $3 million for each center for 6 years, requiring NASA funds ramping to $8 million per year. In addition, NASA's Heliophysics Theory Program (HTP) should be continued as an essential bridge between small grants and the HSC grand challenge investigations, but it may be more effective, as the Heliophysics Science Center program is implemented, to reduce the total number of HTP awards but increase their average size to the range of approximately $400,000 to $600,000 per year. On a complementary front, the development of advanced instrumentation and technology is critical to all of the science areas within NASA's Science Mission Directorate. The technologies required for novel mission designs and instrumentation need a more coherent and better funded NASA program than is currently available, a program that is managed strategically so as to maximize the opportunities to meet strategic goals. It is recommended that NASA increase current annual funding levels for technology, ramping to an augmentation of $4 million per year in order to facilitate urgently needed innovations required for future heliophysics mission implementation.

The *Educate* component reinforces employment opportunities, education and training, and recruitment and public outreach, with the aim of inspiring the next generation of space researchers, training young scientists and engineers, and forging a multi-talented, creative workforce for the future of the United States. Heliophysics is a field with global consequences that are both intellectually stimulating and relevant to society. First, programs supporting solar and space physics faculty and curriculum development are required to maintain a healthy presence in universities. Next, hands-on experience for students is critical in developing a competent workforce. The proposed expansion of the LCAS program under Diversify will provide additional opportunities for graduate programs to attract and train students in the complete mission life cycle. Also, NASA Heliophysics-supported summer schools provide unique opportunities for training and education in the field of heliophysics. In addition, NASA's Earth and Space Science Fellowship (NESSF) program, plays an important role in maintaining graduate support in heliophysics at historic levels, and promotes a strong link between graduate students and NASA mission research. Finally, outreach to the general public and in particular to students who will become the next generation of space scientists and engineers is essential to maintain a thriving field of solar and space physics.

In summary, the Roadmap Team supports the implementation of the low-cost DRIVE initiative into NASA's Heliophysics research program as soon as possible within the current fiscal constraints. The DRIVE initiative capitalizes on the breadth of current programs in Heliophysics and builds for the future. The current HSO is the foundation on which to build. DRIVE makes the most of these existing assets while enabling advances in science and technology that will fuel progress within realistic cost envelopes. By implementing the recommended DRIVE components, NASA can ensure that the next decade will be rich in new observations from diverse platforms, new science harvested from missions and projects, new synergisms between disciplines and platforms, new technologies and theories to enable and inspire future missions and projects, and new talented students to form the future workforce.

The Heliophysics ROSES 2014 Research Program Elements

This Research program directly supports the generation of new knowledge, scientific and technological development and scientific progress in different ways. Theory and numerical simulations, data analysis techniques, data modeling and instrument development are fundamental areas of support. Laboratory work is needed to constrain and quantify basic physical processes, radiative transfer, particle acceleration magnetic reconnection are examples. Low cost access to space is needed to develop the next generation of space hardware. Keeping the program robust was a primary goal of the Decadal Survey report and is a primary goal of this roadmap.

Supporting Research (H-SR)

Heliophysics SR awards are small focused individual research investigations that employ a variety of techniques, including theory, numerical simulation, modeling, analysis, and interpretation of space data. Proposals are accepted across the sub-fields of Heliophysics as well as system-wide investigations. The Heliophysics SR program is intentionally left open to innovative, new investigations within the realm of Heliophysics. The H-SR component of the Research program addresses the Realize portion of the DRIVE initiative.

Technology and Instrument Development for Science (H-TIDeS)

In response to the 2013 DS recommendations for implementing the Diversify portion of the DRIVE initiative, NASA HPD has combined several programs such as instrument and technology development, low-cost access to space (LCAS), the suborbital and sounding rocket programs into a consolidated Technology and Instrument Development for Science (H-TIDeS) program. Proposals are accepted in three general areas (i) science and/or technology investigations that can be carried out with instruments flown on suborbital sounding rockets, stratospheric balloons, CubeSats, or other platforms; (ii) state-of-the-art instrument technology development (ITD) for instruments that may be proposed as candidate experiments for future space flight opportunities; (iii) laboratory research.

The LCAS program is critical for developing new instrumentation and for training the next generation of instrument scientists. Expansion of the program beyond balloons and sub-orbital rockets to include the ISS, commercial reusable suborbital rockets, and CubeSats offers expanded capabilities that are critical for some types of observations. Flexible flight choices also reduce the risk that issues in one area, say the procurement of rocket motors, will have a major impact on the whole LCAS program.

The suborbital programs provide important hands-on training for future engineers and scientists needed by NASA and the nation. The program involves numerous undergraduate and graduate students from diverse institutions. Graduate students can participate in the entire life cycle of a scientific space mission, from design and construction to flight and data analysis — something no other flight program can do. The addition of CubeSats to the suborbital program extends this training ground into satellite development and operation. The Roadmap Team also commends NASA HPD's decision to fully fund six new CubeSat missions through ROSES-13,14.

The NASA sounding rocket program alone has resulted in more than 375 Ph.D.s. In addition, a rocket or balloon experiment offers the chance for younger scientists to gain the project management skills necessary for more complex missions. The combination of unique science, advanced instrument and technology development, and cutting-edge training makes suborbital research a critical item for achieving NASA's science goals. The H-TIDeS component of the Research program also addresses the Educate portion of the DRIVE initiative.

The Instrument and Technology Development (ITD) program allows for pre-flight instrument development and testing. The growing sophistication of new instrumentation creates a problem for some LCAS candidate programs. LCAS cannot easily support a long development program before flight. The ITD program allows laboratory versions of new instruments to be developed and tested reducing schedule and cost risk when the instruments are later proposed to LCAS.

The new Laboratory, Nuclear, Atomic, Plasma Physics (LNAPP) program explicitly supports fundamental physics experiments that are key to heliophysics science. Proposals for laboratory studies of plasma physical processes and experiments that produce chemical, spectroscopic and nuclear measurements that heliophysics measurements and models. The LNAPP program addresses the Integrate portion of the DRIVE initiative.

Guest Investigator (H-GI)
The H-GI program is intended to maximize the scientific output of currently operating Heliophysics missions through support of individual investigations that draw extensively upon the data sets from the missions of the HSO. The focus of the selected research continuously evolves to ensure that the most important questions are identified for recently launched Heliophysics missions and for extended operating missions falling under the Senior Review. The GI component of the Research program addresses the Realize portion of the DRIVE initiative.

Grand Challenges Research (H-GCR)
The new Heliophysics Grand Challenges Research (H-GCR) program currently includes one element: Theory, Modeling, and Simulations (TMS). Theoretical, modeling, and simulation investigations are solicited under other Heliophysics programs, but the TMS element is the only Heliophysics program that is dedicated solely to TMS efforts. It differs from the theoretical/modeling/simulation investigations solicited in other Heliophysics program elements in that it addresses only physical processes that have sufficient breadth and complexity to require the efforts of a critical mass of expertise. Once the DRIVE initiative funding becomes available, additional resources for the Heliophysics Science Centers will be managed through the H-GCR program. NASA and NSF together should work together to create HSCs to tackle the key science problems of solar and space physics that require multidisciplinary teams of theorists, observers, modelers, and computer scientists, with annual funding in the range of $1million to $3 million for each center for 6 years. The recently competed Space Weather Modeling Initiative, out of the H-LWS program, is an example of joint NSF / NASA funding cross-disciplinary research. Following implementation of the HSCs, the H-GCR program will address the Integrate and Venture portions of the DRIVE initiative.

Living With a Star (H-LWS)
The goal of NASA's Living With a Star (LWS) program is to develop the scientific understanding needed to effectively address those aspects of Heliophysics science that affect life and society. To ensure this, the Heliophysics LWS Science program solicits proposals for Focus Teams which coordinate large-scale investigations that cross discipline and technique boundaries leading to an understanding of the system linking the Sun to the Solar System both directly and via the heliosphere, planetary magnetospheres, and ionospheres. In addition, Heliophysics LWS Science supports the Sun-Climate objective whose goal is to deliver the understanding of how and to what degree variations in the solar radiative and particulate output contribute to changes in global and regional climate over a wide range of time scales. Development of Tools and Methods that are needed to achieve the LWS goals are also supported.

A primary goal of NASA's LWS program is the development of first-principles-based models for the coupled Sun-Earth and Sun-Solar System, similar in spirit to the first-principles models for the lower terrestrial atmosphere. Such models can act as tools for science investigations, as prototypes and test beds for prediction and specification capabilities, as frameworks for linking disparate data sets at vantage points throughout the Sun-Solar System, and as strategic planning aids for enabling exploration of outer space and testing new mission concepts. Strategic Capabilities are the development and integration of such models for all the various components of this system. The H-LWS program addresses the Integrate portion of the DRIVE initiative.

Infrastructure and Data Environment Enhancements (H-IDEE)
Progress in space science is sparked by the synthesis of ground- and space-based observations and open data access. If our goal is to understand the Heliophysics System, having access to dipartite data sets is essential. H-IDEE investigations support ground-based facilities that openly provide observations in support of Heliophysics space missions, and extend data services necessary for Heliophysics research efforts. The IDEE component of the Research program addresses the Realize portion of the DRIVE initiative.

Data Centers and Virtual Observatories

The pursuit of heliophysics research requires easy access to HSO data and tools from a distributed set of active archives, each of which has its own architecture and formats: together these data and tools form the core of the Heliophysics Data Environment (HPDE). The NASA Heliophysics Science Data Management Policy, composed with considerable community input, presents an integrated view of the HPDE. Among other things, the HP Data Policy provides a summary of the components of the HPDE, gives a timeline for the data lifecycle, and provides guidelines for documents such as Project Data Management Plans. This document is guiding the implementation of a distributed, integrated, flexible data environment to meet the current and future needs of Heliophysics research.
Two overarching principles also essential to achieving the goals of current Heliophysics programs are:

- Embracing NASA's open data policy that high-quality, high-resolution data, as defined by the mission goals, will be made publicly available as soon as practical, and
- Adhering to the goal of early and continuing independent scientific data usability, which requires uniform descriptions of data products, adequate documentation, sustainable and open data formats, easy electronic access, appropriate analysis tools, and care in data preservation.

Mission data management plans implement the policy. Assembling similar data products from simulations is a work in progress. The GSFC Community Coordinated Modeling Center provides access to space research models, support for implementing new models and provides data from models that have been run in the past. This is an excellent first step in making the essential multi-dimensional modeling tools accessible to the scientific community.

Mission Operations & Data Analysis
MO&DA is embedded as part of the Other Missions and Data Analysis (OM&DA) budget line that exists within each of the four Heliophysics programs. Measurements from the HSO spacecraft provide the "ground truth" to test simulations and models. It is therefore essential that scientific data be properly recorded, analyzed, released, documented, and rapidly turned into scientific results. Stringent budget environments and the associated decline in funding have been somewhat compensated by improvements in information technology making data analysis more efficient; however, the full spectrum of operations and data analysis for missions extends well beyond data analysis.

For heliophysics missions, the mission science teams are assigned the task of ensuring the availability of well-calibrated data throughout the operational phase of the mission. Although the instrumental characterization task is ideally turned into a semi-autonomous process, degradation and other changes of the instrument operations require continuous monitoring and alteration of algorithms and data processing software by cognizant scientists. Access to these data and continuously updating quality factors can be difficult for those not directly connected to the mission teams. The HPD has recognized these patterns and funds additional activities within the MO&DA area to facilitate a smooth data flow. All these activities undergo a regular competitive process, a senior review, where the level of support is adjusted according to the anticipated scientific productivity and mission maintenance requirements.

The Roadmap Team strongly endorses the MO&DA activities within the Heliophysics programs that supports turning raw measurements into robust data products for use in the scientific community. It also endorses the continuation of effective utilization of the calibrated data through competitive grants in the Research program (discussed above). The MO&DA component of the HPD addresses the Realize portion of the DRIVE initiative.

Recommendation No. 1

Implement the DRIVE (Diversify, Realize, Integrate, Venture, Educate) initiative composed of a new, integrated cross-disciplinary effort that will develop more fully and employ more effectively the many experimental and theoretical assets in the Heliophysics Community.

Role of Partnerships

When the HPD teams with other organizations, the opportunities for addressing its scientific goals are increased dramatically. Our science is cross-disciplinary, practical and international, leading to partnership opportunities within SMD, within NASA, with other agencies and with other space-faring nations. Taking advantage of every opportunity will provide for a robust and cost effective flight program.

Intra-NASA Partnerships

There are important synergies between Heliophysics objectives and those in Astrophysics, Planetary, and Earth Sciences, which should be kept in mind and exploited. The Sun remains the archetypical star and thus, the keystone for all of stellar physics and the astrophysics that derives from stars. Understanding the evolution of the Sun is critical for understanding the formation and evolution of all of the solar system objects, and the Sun and Heliosphere have significant dynamic effects on the structure of these objects today. Our understanding of solar influences in the short and long-term on the Earth continues to grow, and space weather and climate are now recognized as essential to understanding Earth. All NASA activities are sensitive to the dynamic influence of the Sun on their assets – from varying atmospheric drag in LEO, UV and energetic particle degradation of solar panels, energetic particle upsets of flight electronics, and radiation hazards from solar energetic particles and galactic cosmic rays.

Heliophysics has a long history of collaborations with Planetary Science Division missions. LADEE, MSL, MAVEN and JUNO are examples of missions with Heliophysics instrumentation. Other important measurements from the Planetary Division will be the solar wind measurements at Pluto from the New Horizons mission. Collaborations with Exploration Systems Mission Directorate (ESMD) are more recent through the Lunar Reconnaissance Orbiter (LRO) program. The ISS offers rich possibilities for remote sensing of the ionosphere and the Sun. Developing capabilities for low cost access to the ISS should be a priority.

National Agency Partnerships

The scientific and programmatic objectives of the NASA Heliophysics program enjoy

Comparative Climatology

Earth, Venus, Mars, and Titan are connected by the Sun that they share. The Sun is a relatively constant star in comparison to other stars that exhibit dramatic pulsations, varying in size and brightness. The total luminosity varies only 0.1%, while the extreme ultraviolet and x-ray radiation can vary by more than a factor of ten over the course of the 11-year solar cycle. Researchers are beginning to realize that variations in solar extreme ultraviolet radiation and energetic particles hitting the top of planetary atmospheres can create a cascade of changes to their chemistry and cloud cover, and can create significant perturbations at high altitudes that might have an impact on planetary climates.

Earth, Venus, Mars, and Titan are rocky bodies within our solar system, each with atmospheres, but distinctly different climates. Comparisons of the atmospheres of these rocky planets and the influence of solar activity have the potential to elucidate the changes in Earth's climate and interplanetary disturbances. The observation of similar and contrasting processes on two or more planets permits a comparison of the chemical and physical principles operating in distinctly different climates.

Comparative Climatology is a growing interest within SMD because it utilizes a multidisciplinary approach involving scientists from Planetary Science, Earth Science, Heliophysics, and even Astrophysics in its search for habitable exoplanets. SMD has supported two annual meetings on this topic, bringing together a wide range of scientists to discuss their investigations into how initial conditions, solar input, and climate feedbacks govern planetary environments and climates.

Looking at climate broadly, comparative climatology focus areas include the thermal radiation on planetary atmospheres and climate forcing by the Sun or parent star, the dynamic chemistry of atmospheres, and clouds, and the role of surface impacts from asteroids and comets on the Earth's climate and the climate of other inner planets. NASA's fleet of Heliophysics, Planetary, and Earth-observing spacecraft can help us increase our understanding of the complex Sun-climate link. Coupling research in the Sun-climate connection with Earth Science models can lead to a general theory of planetary climate, and more accurately envision and model the atmospheres of terrestrial exoplanets. Astrophysicists can then potentially use these models developed through comparative climatology to improve interpretations of growing data on planets around other stars and predict if any given rocky planet around another star is habitable.

In situ observations, space-based measurements, and laboratory studies in Earth science have led to important circulation models that help better understand the interactions of the ocean, atmospheres, land and ice in the climate system. In comparison, missions to other planets are more limited, and only the broadest understanding of the climates of Venus, Mars, and Titan has been possible. Many of the questions that drive the study of Earth's climate are applicable to the other strong synergies with NSF, DOD, DOE, and the Department of Commerce through NOAA. The role of Heliophysics in the National Space Weather Program is addressed in Chapter 5. Often Heliophysics instrumentation can provide near real-time capabilities useful to space weather forecasters. NASA, NOAA and DOD should cooperate in these areas, sharing resources and costs to make data sets available to the groups that need them.

NASA and NOAA have cooperated on providing a follow-on capability to ACE at L1, called DSCOVR. This mission will provide critical space weather information for science, commercial, and military applications.

Heliophysics instruments addressing some of the scientific goals enunciated in this roadmap have found ride opportunities on non-NASA payloads. Two Wide-Angle Imaging Neutral-Atom Spectrometers (TWINS) enabled the three-dimensional visualization and the resolution of large-scale structures and dynamics within the magnetosphere for the first time. In collaboration with the US Air Force, CINDI was supplied by NASA as part of the payload for the Air Force C/NOFS satellite. CINDI is investigating the study of unique plasma bubbles that have the potential to disrupt critical radio signals in the ionosphere.

International Partnerships

International partnerships have long played and will continue to play an extremely important role in addressing heliophysics science imperatives in a highly leveraged and cost-effective manner. During times of constrained budgets, it is critical for Heliophysics to foster and participate in joint missions. Jointly developed missions such as *Ulysses*, *Yohkoh*, SOHO, Cluster, and *Hinode* have significantly improved the quality of many science missions. Strengthening the scientific and technical teamwork between the US and our partners permits activities that could not be achieved separately. Examples of potential international partnerships with high value to the Heliophysics program are listed below.

A JAXA Solar-C mission would be follow-on to the highly successful *Yohkoh* and *Hinode* missions, in which US scientists played a crucial role. During the next twenty years a Solar-C mission would offer the only possibility for US participation in an observatory class solar mission.

The *Outer Radiation Belt Injection, Transport, Acceleration, and Loss Satellite* (ORBITALS) is a Canadian Space Agency- sponsored mission to understand the acceleration, global distribution, and variability of energetic electrons and ions in the inner magnetosphere. Together with other missions, such as NASA's Van Allen Probes, ORBITALS will provide a unique and global view of the inner magnetosphere.

The International Living With a Star (ILWS) program was established in January 2002 by the Interagency Consultative Group (IACG). The charter for ILWS is to "stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun–Earth System as an integrated entity." There are currently more than 33 contributing **agencies and delegates** (ilwsonline.org). ILWS offers opportunities for cooperation between national space agencies in heliophysics.

Technology Development

Significant progress toward meeting the scientific and technical challenges for heliophysics over the coming decades hinges on improving observational capabilities and innovative instrumentation. The Heliophysics Division supports development of technologies for its flight missions via mission specific elements through the three flight programs and the newly initiated Heliophysics Instrument and Technology Development (HTIDeS) element of the Heliophysics Research program.

Heliophysics flight program lines develop medium technology readiness levels (TRL), bringing specific technologies into maturation as required by each mission. For example, technologies developed to enable the SPP mission to fly 20 times closer to the Sun than the Earth and to receive 500 times the solar input are representative of this concept. Key technologies developed for this challenging mission include instruments and a revolutionary carbon-carbon composite heat shield to withstand temperatures over 2500 degrees Fahrenheit.

HTIDeS unifies our development of low- to medium-TRL technologies, as well as instrument feasibility studies and proof of concept efforts. This element of the Research program consists of competitive PI-led efforts, awarded via a peer review process based on the science and technical merits of the submitted proposals, and according to the science priorities of the Heliophysics Division as set by the Decadal Survey. Examples of areas funded through HTIDeS include X-ray and Gamma-ray detectors, extreme ultraviolet mirror coatings, X-ray optics, high-energy particle detectors, energetic neutral atom detectors, and new nano-dust analyzers.

Small satellites, including cubesats, have tremendous promise in addressing many heliophysics science objectives. Although small satellite technologies have advanced rapidly over the last few years, significant technological hurdles still remain. HTIDeS is supporting the development of a number of instrument technologies (e.g., low mass particle spectrometers, and compact interferometers) and working across the Agency to develop the underlying infrastructure. Examples of Agency-wide partnerships for small satellites include investments made by STMD and HEOMD in developing launch systems such as the Cubesat Launch Initiative (CSLI) and deep space operations such as the first test flight, Exploration Mission (EM)-1, of the Space Launch System (SLS). The Heliophysics Division is well poised to take advantage of this new technology.

Cross-Discipline Technology That Enables Future Mission Concepts

Several high-priority heliophysics science questions cannot be addressed with existing technology or resources (*e.g.* the polar structure and dynamics of the Sun and heliosphere, as well as the far reaches of the heliosphere). Before progress can be made in addressing these scientific questions, near-term investments must be made,in critical technologies that enable those missions in the long-term. *Virtually all of these technologies support scientific objectives in planetary science and astrophysics* as well.

The HPD alone is not able to shoulder a number of major developments that have immediate applications across NASA's Science Divisions, other NASA Directorates, or other national agencies, including:

- In-space propulsion (*e.g.* solar sails and solar electric propulsion) for reaching and maintaining critical vantage points in space
- Improved power sources (*e.g.* radioisotope) for near-Sun and deep-space missions
- High-rate, long-distance optical communications for increased data rate of deep space or fleet missions
- Low-cost launch platforms and spacecraft buses
- Lightweight structures and nanotube technology
- Replacement for a Delta II launch capability
- Computational methods and algorithms for multidimensional data analysis and visualization and numerical laboratories for modeling and simulating physical processes and effects
- "Science Discovery Infrastructure" consisting of robust tool sets for mining huge volumes of multidimensional data from all observatories and models and extracting and cataloging features and events
- Onboard science autonomy

Small satellites, including 3- and 6-U CubeSats, have tremendous promise in addressing many heliophysics science objectives within constrained budget environments. Although small satellite technologies have advanced rapidly over the last few years, significant technological hurdles still remain. Small satellites are often manifested as secondary payloads, and are therefore constrained to a handful of common orbits. Small volume and low resource propulsion technologies are needed to enable access to the intended science regimes. Technologies such as microelectromechanical systems and pulsed plasma thrusters exist, but are not yet proven on CubeSats. In addition, the success and popularity of CubeSats stems partly from the ability to use COTS components. Transitioning these low reliability CubeSats for use in NASA missions requires a balancing of the risk of using COTS components vs. cost and spacecraft reliability. Constellations of satellites have tremendous potential and mission concepts have appeared in previous roadmaps, but implementation faces a major obstacle: How to manufacture, integrate and test large numbers of instruments and subsystems within reasonable cost and schedule is a new challenge. The traditional implementation of heliophysics missions is incompatible with constellation builds, and partnering with industry for multiple-copy builds should be explored.

New technologies that should be rapidly employed by heliophysics, but also would equally benefit the other SMD divisions include onboard data compression, fault-tolerant computing, miniaturized electronics and power supplies, low-power sensors, and application-specific integrated circuits. The common thread of these technologies is that they help the Agency accommodate the best possible scientific sensor solutions on upcoming missions. Therefore, it is imperative that heliophysics does not fall behind in applying them.

Instrument Development
Significant progress toward meeting the scientific and technical challenges for Heliophysics over the coming decades hinges on improving observational capabilities and novel instrumentation. The Roadmap Team commends that the HPD has started develop a strong instrument and technology development program. Key areas that would potentially benefit missions in development and the science targets prioritized in this roadmap would include improving detectors in functionality, components, and design. Desirable improvements would include, but are not limited to, the following:

New technologies with reduced noise and insensitivities to heat and radiation for missions approaching the Sun
Improved sensitivity to soft X-ray, UV, EUV and FUV for solar, auroral, and thermosphere remote sensing, but also solar blind/UV blind ENA sensors for magnetosphere and heliosphere imaging
Adaptability of geometric factor, fast pulse-height analysis, and radiation hardness to increase operability during radiation events
Improved sensitivity with larger apertures for in situ charge state and composition analysis at higher cadence
Larger array CMOS detectors for increased spatial resolution and sensitivity to short-wavelength remote sensing
Increased spectral resolution systems and lifetimes for IR, FUV, and EUV for solar and planetary upper atmosphere spectroscopy
Improved robust and light-weight in situ plasma particle measurements

Cross-Disciplinary Technology: Advanced Information Technology
Significant progress has been made over the last decade in establishing the essential components of the heliophysics data environment. However, to achieve key national research and applications goals, a data and computing environment that draws together new and archived satellite and ground-based solar and space physics data sets, as well as computational results from the research and operations communities is needed. We look forward to a continuing growth in science data resources returned from Heliophysics space missions. This explosion, in terms of volume, complexity, and multiplicity of sources will call for new and innovative analysis paradigms to transform that data into knowledge and understanding. Advances in computer science and technology afford vital opportunities to deal with this challenging new environment and enhance science productivity. It is recommended that increased investments be made in the area of heliophysics informatics to include the following:

- Computational methods and algorithms for multidimensional data analysis and visualization
- Numerical laboratories for modeling and simulating physical processes and effects
- “Science Discovery Infrastructure” consisting of robust tool sets for mining huge volumes of multidimensional data from all observatories and models and extracting and cataloging features and events
- Onboard science autonomy for sensor webs drawing from heliophysics observatories
- Coordinated development of a data systems infrastructure that includes data systems software, data analysis tools, and training of personnel
- Community oversight of emerging, integrated data systems and inter-agency coordination of data policies
- Exploitation of emerging information technologies without investment in their initial development
- Virtual observatories as a specific component of heliophysics research-supporting infrastructure, rather than as a direct competitor for research funds
- Community-based development of software tools, including data mining and assimilation
- Semantic technologies to enable cross-discipline data access.

Additionally, to support the theory and modeling components for the Heliophysics Science Centers funded under the DRIVE program, technology development should include

- Development of computational methods and algorithms for multi-dimensional data analysis and visualization
- Numerical laboratories for modeling and simulating

Chapter 5: HELIOPHYSICS: PRIORITY SCIENCE TARGETS

Heliophysics studies the Sun, the heliosphere, and other planetary environments, as an interconnected system. It is truly a cross-cutting discipline, encompassing the science of fundamental physical processes, from the Sun, the major driver of energy input throughout the solar system, to the Earth's upper atmosphere and its direct effect on life on the planet, to interplanetary space weather, to the edges of the solar system where the Sun interacts with the local galactic medium. We use the Heliophysics fleet of spacecraft, (the HSO), to study solar activity and the resulting interplanetary disturbances that are highly variable in location, intensity, and time. Near-Earth space provides a natural laboratory for examining fundamental processes seen at other planets and in other stellar settings. NASA's Heliophysics program provides the research and technological development necessary for the scientific understanding of how space weather affects space exploration and the habitability of Earth and other worlds.

Science Targets

Both detailed in-depth and inductive approaches to science are foundational to the heliophysics strategy. The first is evident in the structure of the science flow down leading to science targets designed to reveal the fundamental workings of the system. The incorporation of new target missions into the HSO and the synthesis and modeling provided by the supporting research program elements enable comprehension of the whole.

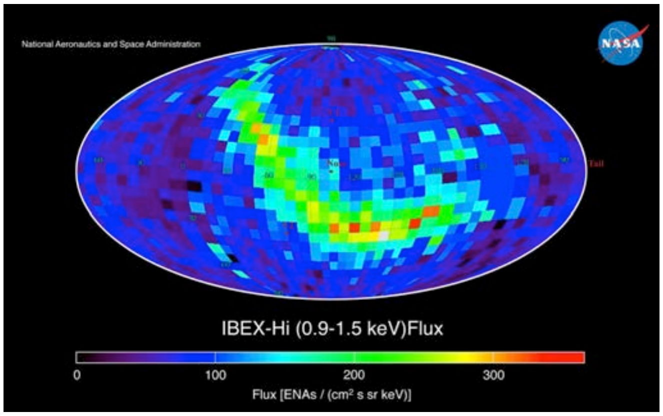
This chapter provides the science background for the highest priority science targets introduced in Chapter 4 and the vision for the heliophysics discipline for the future. A science queue is presented that illustrates the anticipated launch cadences of the STP, the LWS, and the Explorer mission lines which focus upon the highest priority science targets. In the following section, Design Reference Missions (DRMs) are described, the goal of which is to achieve the highest priority science targets (e.g., an IMAP-like mission to further understand and characterize the neutral-plasma interactions between the outer heliosphere and interstellar space). Chosen to fulfill our present gaps in knowledge, their eventual impact will realize a significant advancement in the understanding of the heliophysics system.

As described in Chapter 4, prior to implementing each STP science target, NASA HPD and the Heliophysics Community should assess whether the rationale of the Decadal Survey for prioritizing the STP missions remains in effect. The STP, LWS, and Explorer flight programs represent one element of the full program of exploration, observation, theory, modeling, and simulation that are critical for the development of our knowledge of the past and for extending what is learned to deal with the present and predict the future.

The Heliophysics research strategy continues to be based upon prioritized yet flexible science objectives. The science queue consists of science targets that at this point in their development do not have fixed point designs as their implementation strategies. These priority science targets should, at a later date, be implemented as resources permit through the various Heliophysics flight programs.

Considering both the science and implementation factors, the Roadmap Team has followed the recommendations provided in the NRC Heliophysics 2013 Decadal Survey. Completion of the current program and the DRIVE initiative are described in Chapter 4. The highest priority future science targets are associated with cost categories (i.e., light, small, medium, and large) and placed into a science queue within either the STP or the LWS flight programs consistent with the goals and science objectives of each program. The timing of the projects is based on the recommended launch frequency for each flight program, incorporating the most recent and available budgetary knowledge. All science targets are described in this chapter to the extent that the science queue warrants (i.e., without prescribing implementation or procurement requirements).

Figure XXX indicates launch years for strategic and Explorer missions as presently understood. The missions in development (grey boxes) and the new science targets (purple boxes) are marked with a colored dot, indicating the mission cost class. The boxes are centered on the launch year. The bottom panel lists potential international and intra-NASA partnership opportunities.



Heliospheric Boundary and Solar Wind Plasma Mission

Spinner Spacecraft

Science Target

To understand the global interaction of the outer heliosphere with the interstellar medium and unravel the mechanisms that energize particles throughout the heliosphere.

Science Rationale Summary

The proposed high priority science target heliospheric boundary and solar wind plasma mission (as illustrated by the DS reference mission Interstellar Mapping and Acceleration Probe - IMAP) addresses fundamental questions about the global heliosphere and its interaction with the local interstellar medium as well as the ubiquitous acceleration of energetic particles with unprecedented sensitivity, cadence, and resolution. For these observations, location at the Lagrangian L1 point is optimum, and a comprehensive suite of solar wind and interplanetary instruments are also included to characterize backgrounds in energetic neutral atom (ENA) sensors and to understand the properties of interplanetary disturbances affecting geospace and the heliosphere.

Our heliosphere, its history, and its future in the galaxy are vital for understanding conditions on our evolving planet and its habitability over time. By exploring our global heliosphere and its boundaries, we develop key physical knowledge of the interstellar interactions that influence our home system in its current state, the history and destiny of our solar system, and the habitability of exoplanetary star systems.

The last decade has seen tremendous breakthroughs in our knowledge of the outer edges of the heliosphere and the interaction between the Sun and its local galactic neighborhood. These advances include the crossing of the termination shock by both Voyager spacecraft to the global IBEX and Cassini images of energetic neutral atom emission from the outer heliosphere. IBEX discovered a narrow "ribbon" of ENA emissions encircling the heliosphere (Figure X), and provided direct measurements of interstellar neutral atoms that point to the absence of a bow shock beyond the heliopause. The scientific motivation for a more advanced mission to image the heliospheric boundary and measure the key components of the interstellar gas is compelling and urgent, as the Voyagers will only operate through this decade.

The surprising ENA "ribbon" demonstrates the importance of the interstellar magnetic field in the interaction of the heliosphere with our galactic neighborhood. The physical processes that form ENA spectra and the ribbon are hotly debated because of complex interactions between solar wind, pickup ions (PUIs), and suprathermal particles. The big picture provided by IBEX, complemented by Voyager observations, shows that the asymmetry of the heliosphere is shaped by the surrounding interstellar magnetic field and that the physical processes that control the interaction exist on relatively small spatial and temporal scales (months) that are not currently measured.

Additionally, observations from the HSO contribute dramatically to our understanding of solar energetic particle (SEP) events, of the importance of suprathermal ions for efficient energization, and of the sources and evolution of solar wind, interplanetary magnetic field, and SEPs that impact geospace and the heliosphere. These phenomena are controlled by myriad complex and poorly understood physical effects that must be unraveled to develop a complete picture of particle acceleration and transport and of the causes and impacts of interplanetary disturbances.

Example questions for this science target are:

- How does the structure and interaction of heliospheric boundaries vary and evolve on a wide range of spatial and temporal scales?
- What is the nature of the heliopause and of the interaction of the solar and interstellar magnetic fields?
- What are the composition and physical properties of the surrounding interstellar medium?
- What are the properties, composition, and distributions of samples of matter such as GCRs, ACRs, PUIs, and interstellar dust?
- How are particles injected and accelerated throughout the heliosphere and

heliosheath?

- What are the origins and properties of the suprathermal seed populations of solar energetic particles?

- What are the properties of the solar wind and other interplanetary parameters that drive the Earth's magnetosphere?

Mapping to RFAs, Decadal Challenges, and Previous Roadmap Missions

This investigation primarily addresses RFAs H4 (to understand the interaction of the heliosphere with the interstellar medium), F2 (to understand the plasma processes that accelerate and transport particles), and F3 (to understand the ion-neutral interactions in space). It also addresses F5 (to understand the nature of interactions between waves, turbulence, and particles) and H1 (to understand the causes and evolution of solar activity) and all components of RFA W. This mission follows from the Decadal Survey Science Challenges SH-4 (discover how the Sun interacts with the local interstellar medium) and SH-3 (determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere).

This science target addresses key goals of two design reference missions identified in the 2009 Heliophysics Roadmap:

STP#6 Solar Energetic Particle Acceleration and Transport (SEPAT): Understand how and where solar eruptions accelerate energetic particles that reach Earth.
LWS #9: Heliospheric Magnetics (HMag): Understand the flow and dynamics of transient magnetic structures from the solar interior to Earth.

Measurements

High sensitivity measurements with improved spectral, temporal, and angular range and resolution could include:

- Energetic Neutral Atoms between 0.3-200 keV energy
- Interstellar Neutral Atoms (H, D, He, and O) between 5-1000 eV
- Singly–charged inner source and interstellar pickup ions between 100 eV-100 keV
- Suprathermal Particles:
    - Energy spectra, elemental and isotopic composition between 0.03-5 MeV/n.
    - Charge state composition between 0.03-1 MeV/e
    - Energy spectra of ions and electrons between 5 keV - 3 MeV
- Composition and energy spectra of solar energetic particles (ions and electrons), anomalous cosmic rays, and galactic cosmic rays between ~2–200 MeV/nucleon
- Solar wind
    - Ion distribution functions between 0.1-20 keV/e
    - Electron distribution functions between 0.005 – 2 keV
    - Isotopic, elemental, and charge state composition between 0.1-100 keV/e
- Magnetic field vectors

- Interstellar Dust: mass range (m)> $10^{-13}<m<10^{-10}$ g impact speed (v) $20<v<70$ km/s
- Ly-α photometry

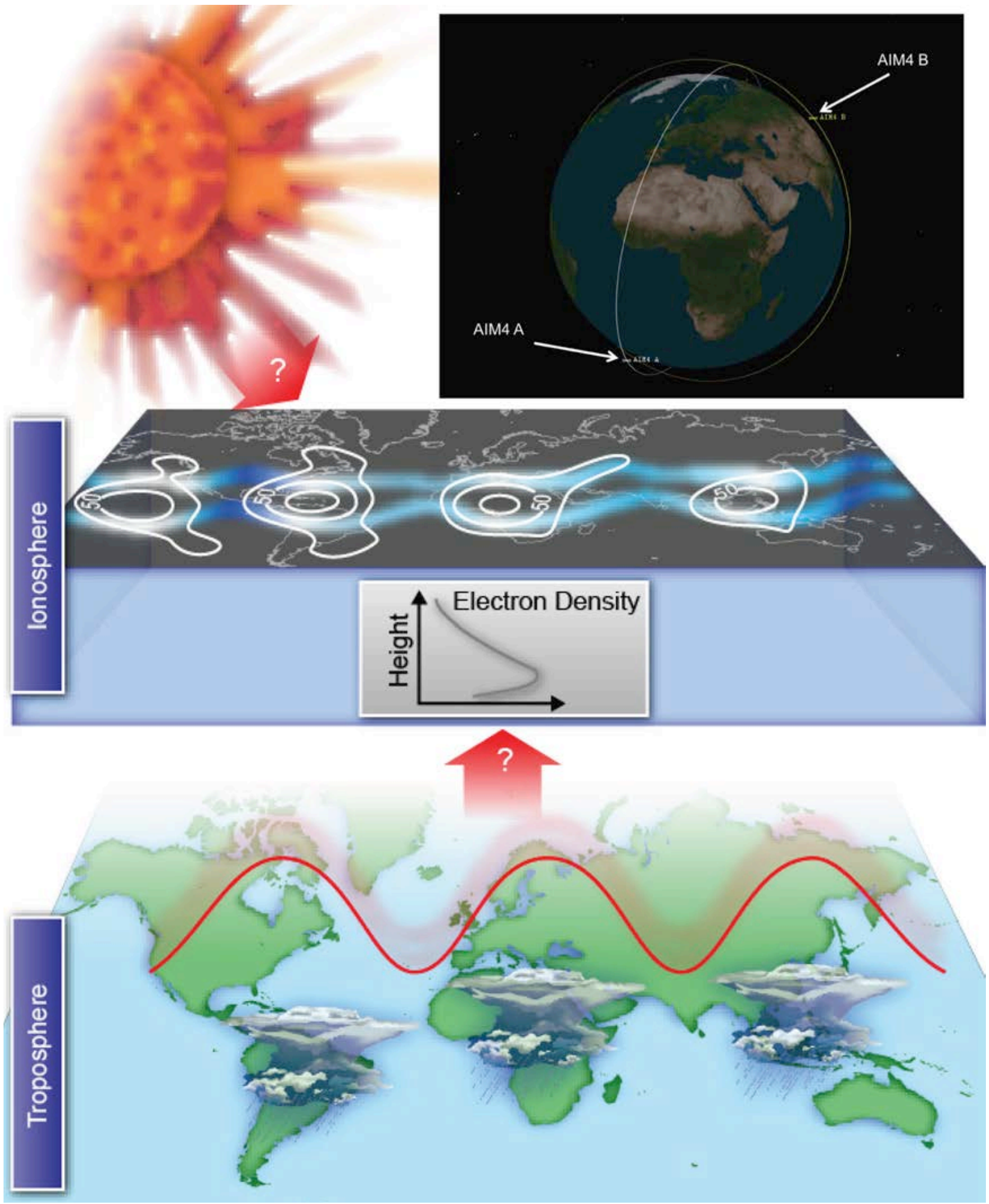
Note that this is not a prioritized or complete list.

Enhancing Technologies

No new enhancing technologies are required as all instruments and spacecraft technologies are straightforward extensions and minor modifications of in-flight instruments and spacecraft subsystems on ACE and IBEX.

Enhancing Pre-mission R&A Focus Areas

- Modeling pickup ion dynamics in the heliosphere and heliosheath
- Multi-fluid ion-neutral coupling near and beyond the termination shock
- Global interaction between the heliosphere and interstellar medium
- Multi-dimensional, time-dependent models of CME initiation, shock formation, coupled with SEP injection, acceleration, and transport



Lower Atmosphere Driving Mission

Science Target

To understand the meteorological forcing from below the upper atmosphere (ionosphere-thermosphere, or I/T) system, by understanding wave coupling with the lower atmosphere, and by understanding how the variability of the lower atmosphere drives neutral gases and plasmas in the I/T system.

Science Rationale Summary

The science target lower atmosphere driving mission (illustrated by the reference mission Dynamical Neutral Atmosphere-Ionosphere Coupling -DYNAMIC) will provide the necessary understanding of fundamental physical processes (e.g., wave dissipation, mean-flow interactions) that underlie the transfer of energy momentum into the I/T system (especially within the critical 100-200 km height regime), and the thermosphere, as well as revealing the ionospheric variability that these waves incur at higher altitudes.

The balance between solar drivers, auroral energy flux and particle precipitation, and forcing from below depends upon local time, season, geomagnetic conditions, and the solar cycle. This dictates a mission design that separates the spatial from temporal influences on the properties of the upper atmosphere. This mission is the first to study the atmosphere as a whole. Atmospheric tides due to persistent tropical rainstorms produce large longitudinal and local time variations in bulk ionosphere-thermosphere-mesosphere (ITM) properties, e.g., temperature, wind, composition, airglow and plasma density. Gravity waves generated by hurricanes or typhoons propagate into the thermosphere. They are postulated as possible causes for a variety of ionospheric phenomena, including plasma bubbles, sporadic-E patches and traveling ionospheric disturbances. Ongoing meteorological capabilities that provide global information on the temperature, winds, and density at the lower boundary, along with evolving modeling capabilities, the global network of ionospheric and upper atmospheric sensors available through NSF and DOD facilities, and international collaborations are all complementary efforts which would enhance the whole atmosphere study.

This mission is urgently needed to address questions that are key to the development of the study of the whole atmosphere system. Our ability to predict and interpret the behavior of the upper atmosphere is currently limited by the large uncertainties in the magnitude and efficiency of the driving forces from below. The response function that converts forcing from below into ITM response needs to be determined. In order to develop the modeling capability to capture our understanding of the physics of the upper atmosphere, this mission is a necessary element.

Example questions for this science target are:

- How does lower atmosphere variability affect geospace?
- How do neutrals and plasmas interact to produce multi-scale structures in the AIM system?
- How does the IT system respond over global, regional, and local scales to changes in magnetospheric inputs?
- How is magnetospheric electromagnetic energy converted to heat and momentum drivers for the AIM system?
- How is our planetary environment changing over multi-decadal scales, and what are the underlying causes?

Mapping to RFAs, Decadal Challenges, and Previous Roadmap Missions

This investigation primarily addresses RFAs H2 (to understand the role of the Sun and its variability in driving change in the Earth's atmosphere, the space environment, and planetary objects) and H3 (to understand the coupling of the Earth's magnetosphere-ionosphere-atmosphere system, and its response to external and internal forcing), as well as F2 (to understand the plasma processes that accelerate and transport particles), F3 (to understand the ion-neutral interactions in space), and F5 (to understand the nature of interactions between waves, turbulence, and particles). It also addresses W4 (to understand and characterize the space weather effects on and within terrestrial and planetary environments). This mission also directly addresses all of the Decadal Survey's AIMI Science Challenges: AIMI-1 (understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over global, regional and local scales); AIMI-2 (understand the plasma-neutral coupling processes that give rise to local, regional, and global scale structures and dynamics in the AIM system); AIMI-3 (understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves, influences the ionosphere and thermosphere; and AIMI-4 (determine and identify the causes for long-term (multi-decadal) changes in the AIM system).

This science target addresses key goals of three design reference missions identified in the 2009 Heliophysics Roadmap:

STP#7: Ion-Neutral Coupling in the Atmosphere (INCA): Understand how neutral winds control ionospheric variability.
LWS#7: Climate Impacts of Space Radiation (CISR): Understand our atmosphere's response to auroral, radiation belt, and solar energetic particles, and the associated effects on nitric oxide (NO) and ozone.
LWS#8: Dynamic Geospace Coupling (DGC): Understand how magnetospheric dynamics provide energy into the coupled ionosphere-magnetosphere system.

Measurements

High sensitivity measurements with improved spatial, temporal, and angular range and resolution could include:

- Limb vector winds between 80 and 300 km altitude
- Limb temperatures between 80 and 300 km altitude
- In situ ion velocity (at 600 km altitude)
- In situ neutral wind velocity (at 600 km altitude)
- Mass spectography of ion (O^+, H^+, He^+) and neutral (O, N_2, O_2, H, He) species
- Altitude profiles of densities:
  - O, N_2, O_2, and H between 110 and 300 km altitude
  - O^+ between 200 and 600 km altitude
- Maps of heat flux, characteristic energies, O/N_2 ratios, O^+, and plasma bubbles

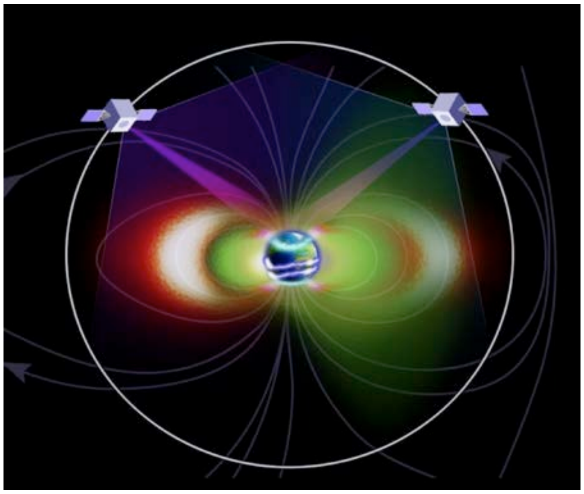
Note that this is not a prioritized or complete list.

Enhancing Technologies

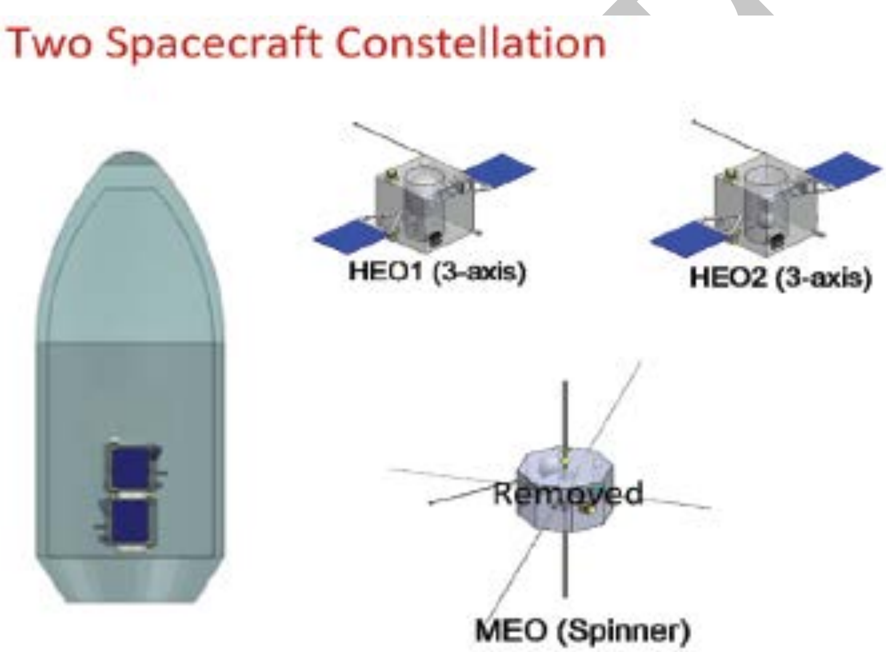
No new enhancing technologies are required as all instruments and spacecraft technologies are straightforward extensions to improve performance and provide additional capabilities.

Enhancing Pre-mission R&A Focus Areas

- Modeling capabilities such as the Whole Atmosphere Community Climate Model (WACCM)
- Enhanced meteorological capabilities which provide global information on the temperature, winds, and densities at the lower boundary
- Global interactions between the magnetosphere and ionosphere



Magnetosphere-Ionosphere-Thermosphere Coupling Mission



Science Target

To determine how the magnetosphere-ionosphere-thermosphere system is coupled and responds to solar and magnetospheric forcing.

Science Rationale Summary

The science target mission magnetosphere-ionosphere-thermosphere coupling mission (illustrated by the DS reference mission Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation - MEDICI) answers two outstanding science questions: (1) How are magnetospheric and ionospheric plasmas transported and accelerated by solar wind forcing and by magnetosphere-ionosphere (M-I) coupling processes? and (2) How do magnetospheric and ionospheric plasma pressures and currents drive cross-scale electric and magnetic fields, which then affect the plasma dynamics? These coupling processes occur over various spatial and temporal scales. The answer to the first question reveals how plasma acceleration and transport processes affect the dynamic, three-dimensional characteristics of the ring current, plasmasphere, and aurorae at a variety of different spatial scales. In addition, the spatio-temporal characteristics of ionospheric outflow phenomena, and the effects on the overall M-I system will be understood. The answer to the second question determines the electrodynamic nature of M-I coupling. Specifically, the cross-scale inter-hemispheric structure and evolution of currents and fields that mediate M-I coupling will be understood, including the mechanisms by which the M-I coupling of electromagnetic fields feed back into the system to affect the plasmas that generated them.

Understanding plasma acceleration and transport processes is fundamental in determining how planetary ionospheres contribute to magnetospheric plasma populations. Indeed, it is in the magnetosphere-ionosphere system where the basic physical processes of particle acceleration and transport have the most direct impact on human activity. These impacts include space weather effects on satellite operations, disruption of electromagnetic signals passing through the ionosphere, and dramatic reconfigurations of the electrodynamic currents that connect the Earth to the heliosphere via the ionosphere and magnetosphere. This science target was formulated specifically to understand how particle acceleration and transport couple the ring current, the plasmasphere, and the aurorae to the ionosphere through current fields and the flow of mass and energy.

Using ENA imaging, the ring current (and near-Earth plasma sheet) characteristics are captured with sufficient temporal and spatial resolution to retrieve the electrical current system that distorts the magnetic field and connects through the ionosphere to produce the electric field. EUV imaging captures the plasmasphere with sufficient temporal/spatial resolution to retrieve cross-scale density structures and the global-to-local electric fields that drive the formation and evolution of these magnetospheric structures. Stereo imaging of the optically thin ENA and EUV emissions enables determination of the three-dimensional structure of pressure, pitch angle, and density, These parameters are then used to reveal energization processes, plasma losses and sources, and to resolve cross-scale currents, fields, and flows throughout this complex and interconnected system. The ionosphere-thermosphere system is to be imaged and measured using multiple wavelengths of far ultraviolet (FUV). Such imaging provides estimates of multiple geophysical quantities in the ionosphere and auroral regions. Critical plasma and magnetic field in situ observations in the cusp and near-Earth plasma sheet plasma are also to be used to determine plasma composition, electron populations, and magnetic field configurations that characterize the plasma environment, during both quiet and storm/substorm intervals. Combined with the imaging techniques, the flow of ionospheric plasma and energy between the ionosphere and magnetosphere is followed, and the acceleration and transport processes throughout the interconnected system are determined.

Example questions for this science target are:

- How is the cross-scale, dynamic, 3D plasma structure of the ring current, plasmasphere, and aurora reshaped by acceleration and transport?

- What controls when and where ionospheric outflow occurs?

- What are the cross-scale, inter-hemispheric structure and timing of currents and fields that mediate M-I coupling?

- How do the M-I coupling electromagnetic fields feed back into the system to affect the plasmas that generated them?

- Does ion outflow escape or remain in the magnetosphere to be recycled?

Mapping to RFAs, Decadal Challenges, and Previous Roadmap Missions

This investigation primarily addresses research focus areas F2 (to understand the plasma processes that accelerate and transport particles), F3 (to understand the ion-neutral interactions in space), H3 (to understand the coupling of the Earth's magnetosphere-ionosphere-atmosphere system, and its response to external and internal forcing), and W4 (to understand and characterize the space weather effects on and within terrestrial and planetary environments). This mission addresses all of the Solar and Space Physics Decadal SWMI Science Challenges, but with greater emphasis on SWMI-3 (determine how coupling and feedback between the magnetosphere, ionosphere, and thermosphere govern the dynamics of the coupled system in its response to the variable solar wind) and SWMI-4 (critically advance the physical understanding of magnetospheres and their coupling to ionospheres and thermospheres by comparing models against observations from different magnetospheric systems).

This science target addresses key goals of two design reference missions identified in the 2009 Heliophysics Roadmap:

LWS #8: Dynamic Geospace Coupling (DGC): Understand how magnetospheric dynamics provides energy into the coupled ionosphere-magnetosphere system.
STP #5: Origins of Near-Earth Plasma (ONEP): Understand the origin and transport of terrestrial plasma from its source to the magnetosphere and solar wind.

Measurements

High sensitivity measurements with improved temporal and spatial resolution could include:

- ENA imaging of the ring current and near-Earth plasma sheet at 1-minute, 0.5 Earth radii resolution
- EUV imaging of the plasmasphere density at 30.4 nm, at 1-minute, 0.05 Earth radii resolution
- Multi-spectral FUV imaging of auroral, ionospheric, and thermospheric processes in the LBH long and short wavebands, at 5-10 km resolution

- Plasma protons and Helium and Oxygen ions to determine in situ densities, temperatures, and velocities from a few eV to 30 keV at ~1-minute resolution
- in situ electron plasma moments from a few eV to 30 keV at ~1-minute resolution
- in situ vector and delta-B (dc and ac) magnetic fields, at ~1-second resolution

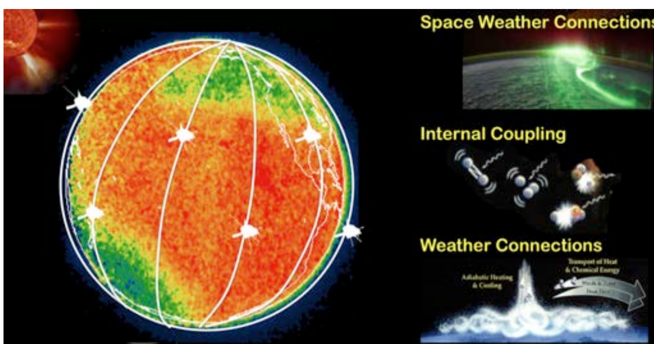
Note that this is not a prioritized or complete list.

Enhancing Technologies

- Support for constellations of small satellites including constellation operations and inter-spacecraft coordination
- Low-power electronics in space
- Miniaturization technologies, enhanced computational capabilities, and autonomous systems

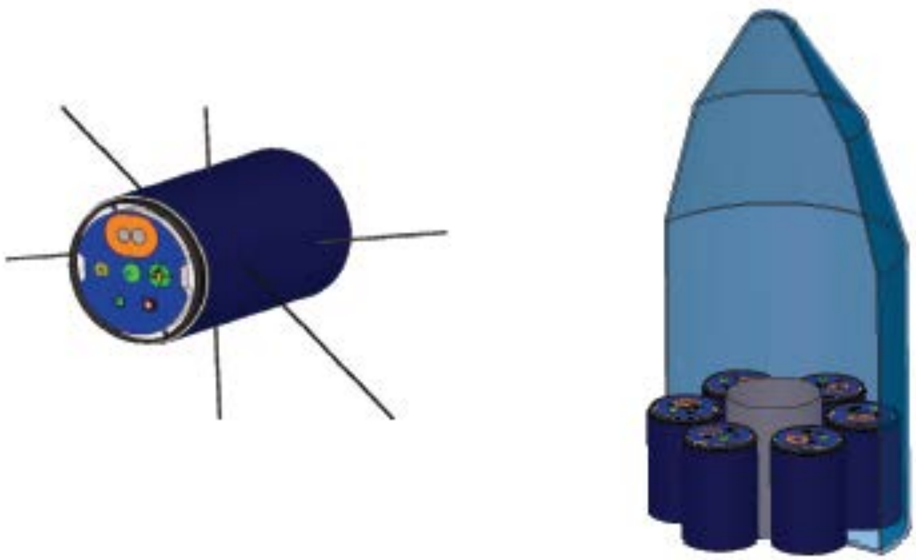
Enhancing Pre-mission R&A Focus Areas

- Multifluid global MHD modeling, incorporating mass outflows
- Dynamic magnetosphere-ionosphere-thermosphere coupling models, including wave, collisional, and particle heating
-



Geospace Dynamics Coupling Mission

Six Spacecraft Constellation



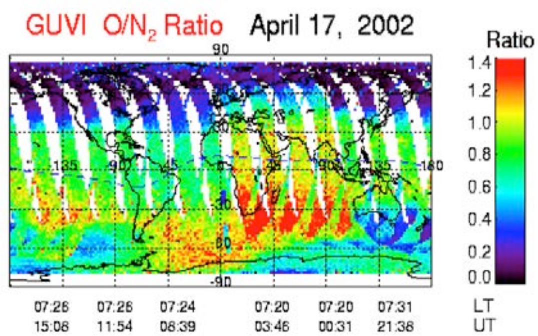
Science Target

To characterize and understand the tightly coupled ionosphere-atmosphere as a regulator of nonlinear dynamics in the geospace system.

Science Rationale Summary

The geospace dynamics coupling mission (illustrated by the DS design reference mission Geospace Dynamics Constellation mission - GDC) is the first mission capable of sustained, multipoint measurements of the key state variables that define the behavior and response of the coupled thermosphere/ionosphere system to magnetospheric drivers over local and global scales.

The geospace dynamics coupling mission reflects a recent revolution in our understanding of the role of the I/T system in the coupled Sun-Earth system of systems. The upper atmosphere and ionosphere, once thought to be passive recipients of these energy inputs, are now known to play a major role (through their tightly coupled interactions) in regulating the response of the entire geospace system to these disturbances. For example, energy inputs to the ionosphere result ultimately in mass outflows to the magnetosphere that determine the severity of the resulting magnetic storm. Changes in neutral atmospheric density or composition as a result of heating are reflected in changes in ionospheric conductance that modify the electrodynamic interaction with the magnetosphere and thus the heat sources to the neutral upper atmosphere. Clues to these interactions have come from single spacecraft observations and from global imaging of a subset of the key parameters but until the flight of the geospace dynamics coupling mission there will be no complete simultaneous characterization of the most important interacting elements - a requirement for identifying couplings and feedbacks between them. In addition, recent research hints at the fundamental importance of latitudinal, longitudinal and hemispheric structures and asymmetries in the dynamic nature of these coupling processes - features that require global observations.



A graphic illustration of major changes in upper atmospheric composition that develop during a strong geomagnetic storm is shown. This view was constructed over a 24-hour period at a fixed local time of ~07:20 hrs. Temporal and spatial changes are mixed due to the rapid time scales involved. Continuing scientific progress requires new ways of constructing simultaneous global patterns of all interacting elements of the system. Credit: NASA TIMED

Example questions for this science target are:

- How do solar wind magnetospheric inputs energize the ionosphere and thermosphere (I-T)?

- How does the I-T system respond and ultimately modify how the magnetosphere transmits solar wind energy to Earth?

- How is solar-wind energy partitioned into dynamical and chemical effects in the I-T system, and what temporal and spatial scales of interaction determine this partitioning?

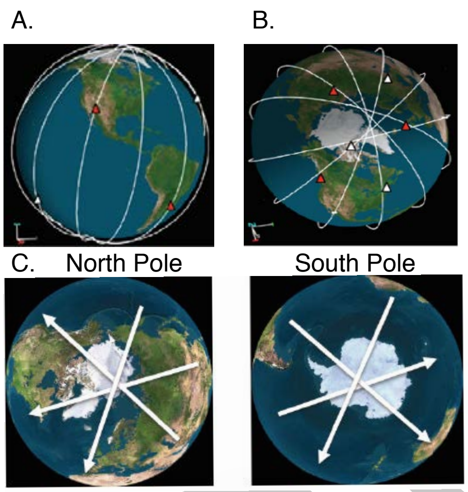
- How are these effects modified by the dynamical and energetic variability of the ionosphere-upper atmosphere introduced by atmospheric wave forcing from below?

Mapping to RFAs, Decadal Challenges, and Previous Roadmap Missions

This investigation primarily addresses research focus areas F2 (understand the plasma processes that accelerate and transport particles), F3 (understand ion-neutral interactions), F5 (understand the role of turbulence and waves in the transport of mass, momentum, and energy), H1 (understand the origin and dynamic evolution of solar plasmas and magnetic fields throughout the heliosphere), H2 (understand the role of the Sun and its variability in driving change in the Earth's atmosphere, the space environment, and planetary objects), H3 (understand the coupling of the Earth's magnetosphere- ionosphere-atmosphere system, and its response to external and internal forcing), and W4 (understand and characterize the space weather effects on and within terrestrial and planetary environments). This mission also addresses the following Heliophysics Decadal Science Challenges: AIMI-1 (understand how the ionosphere-thermosphere system responds to, and regulates, magnetospheric forcing over global, regional and local scales); AIMI-2 (understand the plasma-neutral coupling processes that give rise to local, regional, and global scale structures and dynamics in the AIM system), and AIMI-3 (understand how forcing from the lower atmosphere via tidal, planetary, and gravity waves, influences the ionosphere and thermosphere).

This science target addresses key goals of two design reference missions identified in the 2009 Heliophysics Roadmap:

STP#7: Ion-Neutral Coupling in the Atmosphere (INCA): Understand how neutral winds control ionospheric variability.
LWS#8: Dynamic Geospace Coupling (DGC): Understand how magnetospheric dynamics provide energy into the coupled ionosphere-magnetosphere system.



The figure shows a possible implementation of the GDC mission, with 4-6 platforms in 80° inclination, circular orbits (320-450 km) equally spaced in local time. Three different orbital configurations are given: (A) spread out in latitude for global coverage, (B) dense coverage at high latitudes alternating between poles every 45 minutes, and (C) simultaneous coverage of both poles every 45 minutes. Minimal amounts of propellant relative to the baseline capacity are needed to alternate between these configurations.

Measurements

Gather simultaneous global measurements of plasma and neutral gases and their dynamics, and magnetospheric energy/mass input, using 4-6 platforms in 80° inclination, circular orbits (320-450 km) equally spaced in local time. Each satellite carries an identical suite of instruments. Notional measurements include:

- V_i, T_i, N_i, broad ion composition
- U_n, T_n, N_n, broad neutral composition
- Neutral density
- Vector B, delta B, currents
- Electron distributions, pitch angle (0.05 eV - 20 keV)

Note that this is not a prioritized or complete list.

Enhancing Technologies

- Support for constellations of small satellites including constellation operations and inter-spacecraft coordination.
- Low-power electronics in space
- Miniaturization technologies, enhanced computational capabilities and autonomous systems

Enhancing Pre-mission R&A Focus Areas

- Multifluid global MHD modeling, incorporating mass outflows
- Dynamic magnetosphere-ionosphere-thermosphere coupling models, including wave, collisional, and particle heating

Chapter 6 – Heliophysics Applications

Introduction

Heliophysics is at the forefront of understanding space weather events throughout the heliosphere. The HPD implements the Living With a Star program and a Research program to understand the science of space weather. Studying the Sun, the heliosphere, and other planetary environments as an interconnected system is critical for understanding the implications for Earth, to predict and mitigate the hazards associated with exploration, and to understand the impact of the space environment for the habitability of other worlds. Heliophysics has spacecraft and instruments making critical measurements of solar phenomena such as solar flares and coronal mass ejections (CMEs) and to study the effects on planetary space environments. NASA and NOAA work together (with other government agencies through the National Space Weather Program) on satellite development, transitioning research to operations, data processing, and modeling that inform and improve space weather predictions.

The term "space weather" refers to the magnetic disturbances and high radiation levels that result from the dynamically changing conditions on the Sun and in the solar wind that have impacts throughout the heliosphere including the near-Earth environment. Auroras, power outages, and radio blackouts are some of the manifestations of space weather events that we experience on Earth. In space, high-velocity solar energetic particles strewn from the Sun can cause spacecraft damage, resulting in temporary operational anomalies, critical electronics malfunctions, degradation of solar arrays, and optical systems failures. Further, space radiation is a hazard to astronaut health. However, space weather science is not just limited to Earth. Space weather impacts can be seen throughout the solar system and the emerging science of interplanetary space weather forecasting is crucial to NASA's human and robotic exploration objectives beyond Earth's orbit.

Until recently, space weather forecasting for the near-Earth environment was limited, while forecasting space weather for other planets was simply unthinkable. This began to change, and changed dramatically in 2006 with the launch of the twin Solar Terrestrial Relations Observatory spacecraft followed almost four years later by the Solar Dynamics Observatory. These three spacecraft now maintain near full coverage of the Sun, monitoring active regions, flares, and CMEs. This fleet comprised of STEREO, SOHO, and SDO provide constant 360-degree observations of the Sun. Forecasters now have an unprecedented 3-dimensional view of storms approaching not only Earth, but also other planets as well. As such, interplanetary space weather prediction is now a fast-growing discipline. The ability to predict the onset of distant storms has applications in three areas:

1) Human Safety: Warning astronauts to take cover when solar storms are approaching. Without this capability, long-distance human exploration of space may

prove impracticably dangerous.

2) Spacecraft Operations: Warning to spacecraft operators to take precautions when solar storms are approaching. A few choice hours in "safe mode" could preserve key systems impossible to repair from millions of km away.

3) Science Targets of Opportunity: Alerting distant probes to when solar storms are about to hit planets, asteroids, etc., revealing for the first time how these targets interact with the Sun. For example, a Mars orbiter activating key sensors at precisely the right moment could catch a CME stripping a parcel of atmosphere away from the red planet.

At the moment, humans are confined to low Earth orbit, where the terrestrial magnetic field and the body of Earth itself provide substantial protection against solar storms. Radiation health experts stress that accurate forecasting is urgently needed to support extravehicular activity. Astronauts need to know when it is safe to leave their spacecraft or habitats. Eventually, though, astronauts will travel to distant places where natural shielding is considerably less. Research has shown, in a worst-case scenario, astronauts exposed to solar particle radiation can reach their permissible exposure limits within hours of the onset of an event. Surface-to-orbit and surface-to-surface communications are sensitive to space weather storms in the ionospheres, thermospheres, and mesospheres of planetary bodies. Aerobraking utilizes the thermosphere and mesosphere of a body and depends on knowledge of upper atmosphere neutral density. Dust grain adhesion on astronaut suits and instrumentation is a plasma physics problem that is not well understood or resolved. NASA’s new long-term initiatives to send astronauts to asteroids and Mars safely, directly relies on our ability to successfully understand, predict, and mitigate impacts of interplanetary space weather.

Impacts of Space Weather

Society & Near-Earth space assets

As society becomes increasingly dependent on technologies that are affected by space weather, our vulnerabilities have become more obvious and more worrisome. A report issued in December 2008 by the Space Studies Board of the U.S. National Academies entitled, “Severe space weather events — Understanding societal and economic impacts: A workshop report,” estimates that the economic cost of a severe geomagnetic storm could reach U.S. \$1– \$2 trillion during the first year alone, with recovery times of 4–10 years. These long recovery times could result from severe damage to large power transformers and other hard-to-replace facilities. Such a scenario would result from a storm of the magnitude of one that occurred in September 1859.

Deep space assets and human exploration

Within NASA there is a need for space weather awareness and forecasting that extends throughout the solar system. Recent observations from LRO/CRATER and MSL/RAD characterize the radiation environment of the Moon and Mars respectively. Extending forecasting capabilities will be necessary as humans venture beyond low earth orbit.

The wide reach of the Sun's influence is why Heliophysics is at the crossroads of so many different disciplines. Earth scientists factor the Sun into studies of weather and climate. Astrophysicists scrutinize solar plasmas and magnetism to better understand stars, black holes and other objects across the galaxy. Planetary scientists study the magnetospheres and ionospheres of other planets, which are directly correlated with Heliophysics studies. Heliophysics also has close ties to other NASA Mission Directorates, including Aeronautics, where heliophysics characterization of the Earth's ionosphere and radiation belt environment is needed to design reliable electronic subsystems for use in air and space transportation systems. Exploration Systems relies on heliophysics science to define the radiation and plasma environment to enable exploration of interplanetary space by humans. Space Flight needs to understand surface-charging environments that affect launch vehicles, spacecraft, and space weather events that affect the safety of humans. Protection of humans in space is an operational activity within NASA's Human Exploration and Operations Mission Directorate, which supports the International Space Station. The HPD also collaborates with the Space Radiation Analysis Group at NASA's Johnson Space Center, which is responsible for ensuring that the radiation exposure of astronauts remains below established safety limits. HPD works closely with these intra-agency groups to develop a space weather strategy that meets NASA's needs and supports our presence in space.

Agencies and organizations
To leverage resources and extend the reach of our science results, partnerships are the most viable method for satisfying the national need for space weather knowledge and observations. Interagency coordination in space weather activities has been formalized through the National Space Weather Program Council, which is hosted by the Office of the Federal Coordinator for Meteorology. This multiagency organization comprised of representatives from 10 federal agencies and functions as a steering group responsible for tracking the progress of the National Space Weather Program. External constituencies requesting and making use of new knowledge and data from NASA's efforts in Heliophysics include the FAA, DOD, and NOAA.

Presently, this is accomplished with the existing fleet of NOAA satellites and several NASA scientific research satellites. Space weather "beacons" on NASA spacecraft provide real-time science data to space weather forecasters. Examples include ACE measurements of interplanetary conditions from L1, real-time radiation belt conditions from the Van Allen Probes, CME alerts from SOHO, and STEREO beacon images of the far side of the Sun. NASA will continue to cooperate with other agencies to enable new knowledge in this area and to measure conditions in the space environment critical to both operational and scientific research.

To facilitate and enable this cooperation, the Science Mission Directorate makes its Heliophysics research data sets and models continuously publicly available to industry, academia, civil and other government space weather interests via existing Internet sites. These include the Heliophysics Virtual Observatories and the Combined Community

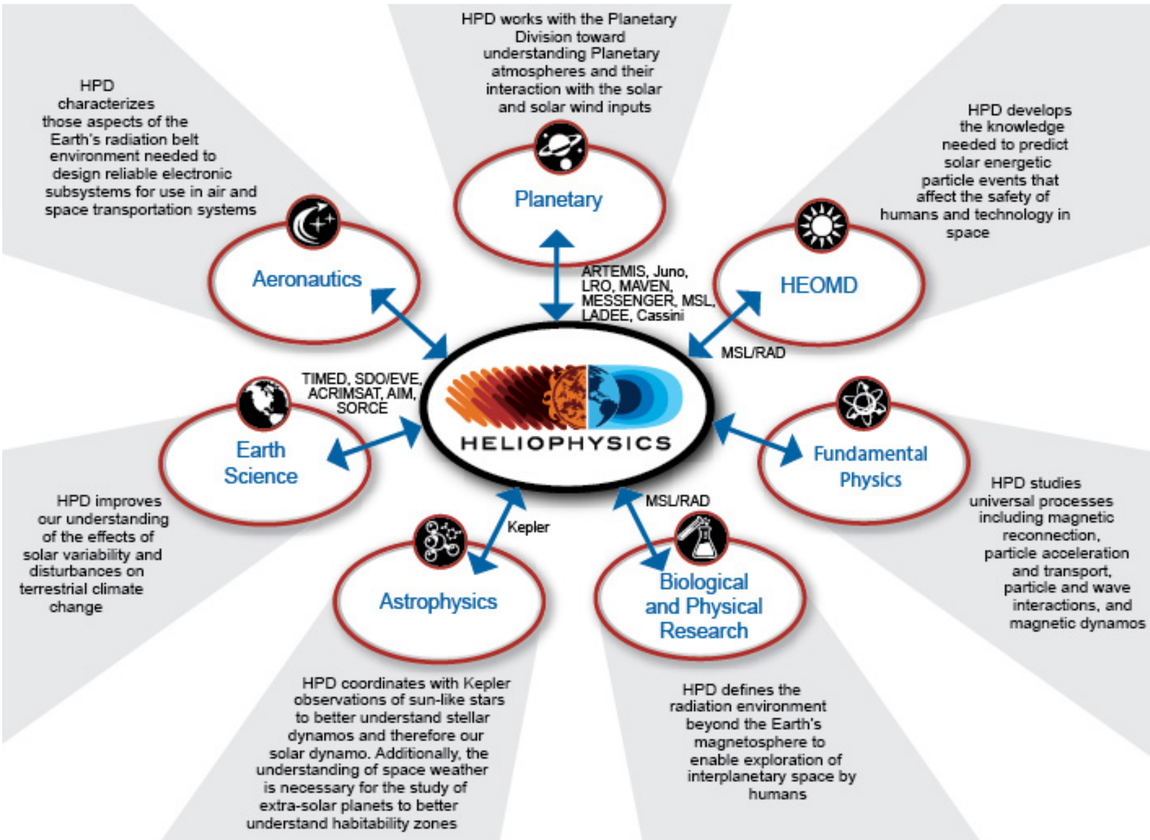
Modeling Center an interagency collaborative activity involving the NSF, NOAA, and the DOD.
While NOAA and USAF are responsible for space weather forecasts at Earth, NASA has a growing need for interplanetary space weather forecasts. The HPD provides space weather products to other NASA directorates and is actively involved in developing models that can provide forecast at different locations in the heliosphere.

Space weather is of international importance and NASA participates in a number of international efforts to enhance the science. NASA is the US representative on the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) for their Space Weather agenda. This includes leadership of the International Space Weather Initiative (ISWI), a United Nations initiative to advance space weather science by establishing a space weather data and modeling network throughout the world. NASA is one of six space agencies in the Steering Committee of International Living with a Star (ILWS), which includes 31 space agencies worldwide. ILWS provides world leadership for the coordination of heliophysics missions, observations, and understanding.

Future cooperation
Close cooperation between NASA, NOAA and USAF on space weather assets will be needed during the coming decades. This Roadmap strongly supports cooperation between agencies as the only effective strategy for making progress on space weather forecasting during times of tight federal budgets. It will be impossible for NASA to assume responsibility for all of the near real-time observations that are needed for the next generation of space weather forecasting tools.

As NASA's exploration continues to extend beyond near Earth orbit, small autonomous space weather instrumentation packages could be utilized. The science and technology to develop this capability is the responsibility of the HPD.

The role of continued observations from L1, in particular, needs to be addressed at an interagency level. The Heliophysics science community recognizes the importance of upstream measurements. The DSCOVR mission is a good example of how NASA and NOAA are working together to address gaps in critical measurements that could arise due to the aging ACE spacecraft. In a similar way, the loss of the white light coronagraph on SOHO would have an adverse impact on the ability to identify and track Earth-impacting CMEs. Use of low-cost options should be explored to satisfy this observational requirement.



HPD works with the Planetary Division toward understanding Planetary atmospheres and their interaction with the solar and solar wind inputs
Planetary
ARTEMIS, Juno, LRO, MAVEN, MESSENGER, MSL, LADEE, Cassini
HPD characterizes those aspects of the Earth's radiation belt environment needed to design reliable electronic subsystems for use in air and space transportation systems
Aeronautics
HPD develops the knowledge needed to predict solar energetic particle events that affect the safety of humans and technology in space
HEOMD
MSL/RAD
HELIOPHYSICS
TIMED, SDO/EVE, ACRIMSAT, AIM, SORCE
Earth Science
HPD improves our understanding of the effects of solar variability and disturbances on terrestrial climate change
Fundamental Physics
HPD studies universal processes including magnetic reconnection, particle acceleration and transport, particle and wave interactions, and magnetic dynamos
Kepler
Astrophysics
MSL/RAD
Biological and Physical Research
HPD coordinates with Kepler observations of sun-like stars to better understand stellar dynamos and therefore our solar dynamo. Additionally, the understanding of space weather is necessary for the study of extra-solar planets to better understand habitability zones
HPD defines the radiation environment beyond the Earth's magnetosphere to enable exploration of interplanetary space by humans

Chapter 7

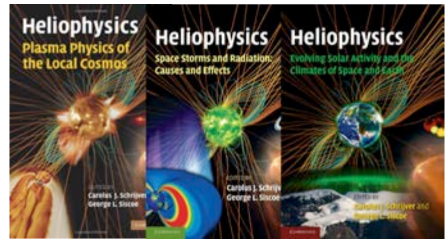
HELIOPHYSICS: EDUCATION AND PUBLIC OUTREACH

For nearly 50 years, NASA's journeys into air and space have developed humankind's understanding of the universe around us and the planet on which we live. These accomplishments share a common genesis, education. Previous experience has shown us that implementing exciting and compelling NASA science missions are critical to inspiring the next generation of explorers, scientists, and engineers. Through partnerships with the Agency's mission directorates; other Federal agencies; private industry; and scientific research and education organizations we leverage NASA's unique resources to engage the public, inform teachers, and excite students.

In May 2010, NASA Administrator Charles Bolden commissioned a study to investigate ways of strategically refocusing and leveraging Agency-wide education and public outreach programs to make the greatest possible impact on Science, Technology, Engineering, and Mathematics (STEM) education, science literacy and the training of the technological workforce of the future required to preserve US competitiveness in the global marketplace. The resulting 2011 Education Recommendation Report lays out a plan to make the best use of constrained E/PO resources by targeting key aspects of these national challenges rather than spreading resources too thinly, by making full use of Education partnerships, and by providing integrating structures that allow NASA to gain from synergies between the highly successful E/PO programs of directorates and centers while eliminating overlaps and phasing out efforts that are not aligned with strategic Agency goals.

The report placed an increased emphasis on the effective use of communication to support all other aspects of the E/PO program allowing NASA to use its unique content to capture public interest, train educators, and attract students into STEM areas. Effective and proactive communication channels geared to target audiences are key to making maximum use of education and outreach content developed in Heliophysics and throughout the Agency.

The 2013 NRC Decadal Survey for Heliophysics, discussed the important role Heliophysics E/PO plays in producing stunning content that inspires the general public and attracts students to participate in STEM fields, but also identified a number of important education and workforce issues that are considered later in this chapter.



The Science Mission Directorate (SMD) implements NASA's three major education goals in coordination with NASA's Education and Communication Offices:

- Strengthen NASA and the Nation's future workforce
- Attract and retain students in STEM disciplines
- Engage Americans in NASA's programs

SMD plays an essential role in NASA's Strategic Education Framework to "inspire, engage, educate and employ." Using programmatic tools and resources, SMD continues to build strategic Education and Public Outreach (E/PO) partnerships to enhance the Nation's formal education system and contribute to the broad public understanding of STEM. SMD's E/PO programs share the results of our missions and research with wide audiences. In addition, E/PO programs promote inclusiveness and provide opportunities for students with disabilities, minority universities, and other target groups to compete for and participate in science missions, research, and education programs. The combined emphasis on precollege and pre-workforce education, diversity, and increasing the general public's understanding and appreciation of STEM areas encompass all three major education goals.

NASA's Strategic Education Framework utilizes three main areas of E/PO (defined below): Formal Education, Informal Education, and Public Outreach. A key ingredient in each of these areas is communication. The effective use of communications delivers visually stunning and intuitive materials through appropriate channels to the intended audiences for maximum impact.

- **Formal Education** takes place primarily in the classroom setting involving smaller audiences with more contact time resulting in a deeper understanding of the material. This typically involves a formal curriculum with textbooks, teacher workshops, and course work at the K–12, undergraduate, and graduate levels. A particular emphasis that is developing for a more tightly focused E/PO program is on middle school educator training. Middle school is a critical time interval during which students often make the decision not to participate in STEM fields. Intervention is needed to keep them in the pipeline. Educator training provides a means of reaching a much larger group of students with thrilling and inspiration content.

- **Informal Education** involves settings outside the classroom such as programs held at museums, libraries, or parks. There is usually a much larger audience, less contact time with participants, and information is broader in scope and is aimed at a more general audience.
- **Public Outreach** events are unique opportunities for providing larger audiences with relatively new information that excites interest and stimulates curiosity. Efforts tend to make the information accessible and relevant, and to reach out to people and relate it to their everyday lives.

FORMAL EDUCATION: HIGHER EDUCATION

Heliophysics Summer School

Heliophysics, as a coherent intellectual science discipline, is being taught for the first time through a 3-year summer school series that started in 2007. The school focuses on select fundamental plasma-physical processes that are behind many aspects of space weather, including energetic particle generation and its effects, and addresses the climate systems formed by the solar dynamo and the Earth's atmosphere.

The 3-year Summer School had two principal aims: (1) to educate close to 100 students (selected through a competitive process) and two dozen teachers in heliophysics as a coherent science through highly interactive seminars and hands-on working groups, and (2) to produce a series of textbooks from which heliophysics may be taught in the future at universities around the world. The first of these textbooks was published in 2009; the second and third in 2010. Problem sets and labs developed during the fourth Summer School in 2010 were made available through the internet as supplemetal teaching materials. The Summer School was then converted into a testbed for teaching subsets of the textbook and supplemental materials.

The seventh heliophysics Summer School was held in Boulder, CO, July 12–19, 2013. NASA and the University Corporation for Atmospheric Research Visiting Scientist Programs sponsor the Summer School. In 2009, the NASA Living With a Star (LWS) program joined with the UCAR Visiting Scientist Programs (VSP) to create the *Jack Eddy Postdoctoral Fellowship program*.
For more information, see: http://www.vsp.ucar.edu/Heliophysics/.

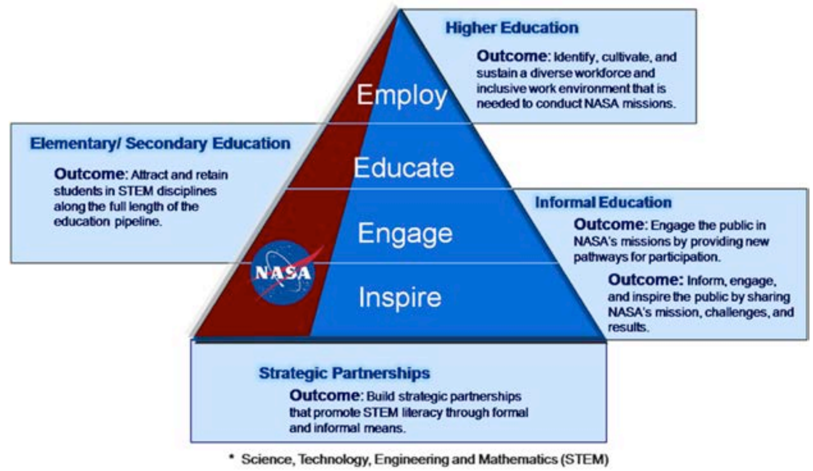
FORMAL EDUCATION: MIDDLE-HIGH SCHOOL EDUCATOR TRAINING

The ***Heliophysics Education Ambassador (HEA) Program*** focuses on delivering learning experiences in the Earth, Space and Physical Sciences for educators working with middle and high school students. The idea is for educators in the HEA workshops to implement lesson plans in their own classrooms and train other teachers to use heliophysics science and education resources at local and regional professional development conferences.

The program consists of a week-long training workshop with support for the next several years through telecons and other forms of electronic communication. The workshops make use of educational materials developed by the E/PO programs of Heliophysics missions, including: AIM, IBEX, MMS, Van Allen Probes, SDO, THEMIS, TIMED, and Voyager.

The first workshop took place in Anchorage, Alaska in June 2009. Two others in Chicago, IL followed this workshop in 2010 and 2011 each supporting 25-30 education ambassadors. A fourth reunion workshop was held in Chicago in 2012.

For more information, see
http://cse.ssl.berkeley.edu/hea/



EDUCATION STRATEGIC FRAMEWORK

This framework provides a conceptual basis around which the NASA education portfolio is organized. Each category represents a pool of participants. Some of the participants in the pool are drawn by NASA's educational activities into the next level creating a pipeline feeding progressively upward into STEM careers and creating the workforce needed to carry out NASA's mission. Outreach, though not pictured here explicitly, directly connects to many aspects of NASA's education efforts by providing the inspiration and excitement that leads participants to seek out educational activities. A major change in the strategic framework since the 2009 Heliophysics Roadmap is depicted by the red portion, which represents NASA's more focused education efforts. The blue portion, which ensures coverage of the entire STEM education spectrum, is addressed by strategic partnerships with educational organizations.

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While there are key differences between these three areas, substantial connections and overlaps exist necessitating the joint efforts of SMD, and the Offices of both Education and Communications. The Office of Education coordinates formal and informal education programs led and supported by the Mission Directorates while the Office of Communications is responsible for public outreach and public affairs. The ability to recognize these intersections and take advantage of the opportunities they provide is essential to maximizing the value of E/PO programs and activities.

The HPD has made a remarkable impact through the commitment of substantial funds for E/PO programs and activities over he last decade or more. E/PO is an important element of the flight and Research programs, and, moving forward, we envision a more coherent and more integrated set of activities aligned with Heliophysics programmatic content.

This reflects the evolution of heliophysics science to a system-wide approach of studying the Sun and its effects throughout the solar system. As a result, the Heliophysics community will continue to contribute to a broad public understanding of the science and its relevance to society. Community participation is vital to the success of the Heliophysics E/PO program.

The HPD goal is to ensure a coordinated, balanced, and broad portfolio of activities in formal education, informal education, and public outreach through full and open competition. To achieve this goal, the Heliophysics E/PO program is currently being realigned to maximize limited E/PO funding and resources and to correspond with a new SMD E/PO approach.

Significant opportunities exist to extend the impact of heliophysics science and related mission activities to engage and inspire students in formal education settings, audiences at informal learning centers, and the general public across the Nation and the world via the press and other communication outlets. Therefore, it is necessary to target the following four strategic communication objectives:

- Seek opportunities to increase and maintain public awareness of heliophysics science through activities, materials, and events.
- Engage students and sustain their interest in heliophysics-related STEM subjects.
- Collaborate with and engage educators to enhance their knowledge of heliophysics-related subjects and activities.
- Build awareness among students, educators, and the public on the diverse range of career opportunities related to heliophysics science and missions.

Blue Bayou Sunset

OUTREACH
"Sun as Art" Traveling Exhibit

The Sun as Art traveling exhibit is a collection of images taken by the Solar Dynamics Observatory, most of them in extreme ultraviolet light. The images are selected to bring dramatic, breathtaking, and unusual views of our sun to a broader audience. These images present new ways of looking at the Sun as seen from space. Many images are reproduced without alteration capturing spectacular solar displays; in others, changes in color tables or manipulation of the images themselves create captivating artistic effects.

The exhibit opened at the Maryland Science Center in Baltimore, MD in February 2012.

A slide show of images in the exhibit can be found at http://sdo.gsfc.nasa.gov/gallery/art.php.

Establishing partnerships between Heliophysics missions and other successful E/PO programs that utilize established infrastructures and leverage existing resources is essential to the development of a dynamic and effective E/PO program with national and international impact. Through these partnerships, Heliophysics E/PO can avoid duplicating efforts and ensure E/PO funds are invested for highest impact.

A strategic goal of Heliophysics (and SMD) is to maintain the healthy and diverse workforce needed to conduct NASA missions. To make this happen, close linkages between NASA's education programs and recruiting and hiring activities are essential. The pipeline developed in NASA's Education Framework results in more students entering STEM fields and ultimately a skilled and capable workforce for NASA.

The most recent information on the Heliophysics workforce is provided by the NRC 2013 Heliophysics Decadal Survey. Though PhD production has increased over the past decade, advertised positions in heliophysics have decreased. In particular, advertised academic faculty positions reached a decadal low in 2010, the last year surveyed. The oppositely directed trends in PhD production and numbers of faculty that train them, create a need for strengthening heliophysics curriculum and other educational resources and sharing them nationwide. However, despite this general upward trend in PhD's, there has been steady erosion in the numbers of *experimentally* oriented scientists and engineers that are key to NASA's future missions. Hands-on experiences in hardware development (such as might be provided by participation in Low-Cost Access to Space or CubeSat programs) are critical for educating graduate students in this area. Summer schools for graduate students serve a complementary role in providing important hands-on training in modeling and data analysis particularly those offering an integrative view of the entire system Sun to Earth. Another key element in training a future workforce in Heliophysics is a strong fellowship program. For the past 30 years graduate fellowships have been provided through the NASA Graduate Student Research Program (GSRP). However, with the ending of the GSRP program in 2012, NASA's Earth and Space Science Fellowship (NESSF) program will take on the important role of maintaining Heliophysics graduate support. The Decadal Survey recommends that this be at comparable levels to the previous program to ensure strong linkages between graduate training and mission science.

In the modern age, space exploration continues to thrill the public with new discoveries that help them build a better understanding of the Sun, near-Earth space, the solar system, and the universe. Heliophysics E/PO will continue to play a leading role as an innovator in the formal education arena (K–12 and postsecondary), in museums and science centers, through high-production-value films, and rich website environments, ensuring that a significant fraction of the U.S. population retains its abiding fascination with space exploration and discovery.

Appendix A: NASA Strategic Goals and Objectives, Science Goals, Decadal Survey Priorities, and Missions

NASA Strategic Goal: Expand the frontiers of knowledge, capability, and opportunity in space.

NASA Objective	Science Goals	Decadal Survey Priority	Mission
Understand the Sun and its interactions with the Earth and the solar system, including space weather.	1. Explore the physical processes in the space environment from the Sun to the Earth and throughout the solar system. 2. Advance our understanding of the connections that link the Sun, the Earth and planetary space environments, and the outer reaches of our solar system. 3. Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.	(a) Determine the origins of the Sun's activity and predict the variations of the space environment. (1, 3) (b) Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs. (2, 3) (c) Determine the interaction of the Sun with the solar system and the interstellar medium. (1, 2) (d) Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe. (1, 2)	ACE (a, c, d) AIM (b) ARTEMIS (d) CINDI (b) Cluster-ESA (d) Geotail-JAXA (d) GOLD (b) Hinode-JAXA (a, d) IBEX (a, c) ICON (b) IRIS (a, d) MMS (b, d) RHESSI (a, d) SDO (a, d) SET-1 SOHO-ESA (a, c, d) Solar Orbiter-ESA (a, c, d) Solar Probe Plus (a, c, d) STEREO (a, c, d) THEMIS (d) TIMED (b) TWINS (b) Van Allen Probes (d) Voyager (a, c, d) Wind (a, c, d)

Appendix B: Status of NRC Decadal Survey Recommendations and/or National Priorities

	Program/Mission Concept	Class*	Recommendation	Status
Heliophysics				
Heliophysics Explorer Program	Small	Accelerate and expand program	Next AO NET 2016	
	Ionospheric Connection (ICON)	Small	Complete missions in development	In formulation. LRD: 2017
	Global-scale Observations of the Limb and Disk (GOLD)	Small	Complete missions in development	In formulation. LRD: 2017
	Explorers and Missions of Opportunity	Small	High priority science investigations, filling focused, but critical gaps in our knowledge	2021, 2024, 2026, 2029
Solar Terrestrial Probes Program (STP)	--	Restructure as higher cadence medium PI-led program	STP-5 LRD NET 2023	
	Magnetospheric Multiscale (MMS)	Large	Complete missions in development	In development. LRD: 2015
	Heliospheric Boundary and Solar Wind Plasma Mission	Medium	Advance our understanding of the interstellar boundary and its interaction with the interstellar medium through remote sensing observation and unravel the mechanisms by which particles are energized.	Planning
	Lower Atmosphere Driving Mission	Medium	Understand how lower atmospheric wave energy drives the variability and structure of the near-Earth plasma.	Planning

	Magnetosphere-Ionosphere-Thermosphere Coupling Mission	Medium	To determine how the magnetosphere-ionosphere-thermosphere system is coupled and responds to solar and magnetospheric forcing.	Planning
Living With a Star Program (LWS)	--	Start next LWS mission by end of the decade	Next LWS AO post 2020	
	Space Environment Testbeds (SET-1)	Small	Complete missions in development	In development. LRD: 2016
	Solar Orbiter Collaboration (SOC)	Medium	Complete missions in development	In development. LRD: 2018
	Solar Probe Plus (SPP)	Large	Complete missions in development	In development. LRD: 2018
	Geospace Dynamics Coupling Mission	Large	To characterize and understand the tightly coupled ionosphere-atmosphere as a regulator of nonlinear dynamics in the geospace system.	Planning

- As determined by the 2013 Heliophysics Decadal Survey, which defines mission class as follows: Small (Explorer Class) - \$50M-\$300M; Medium - \$300M-\$600M; and Large - >\$600M

Appendix C: Current Heliophysics Missions

ACE
Advanced Composition Explorer

Launch Date: August 27, 1997
Phase: Extended Operations
Website: http://www.srl.caltech.edu/ACE

ACE observes particles of solar, interplanetary, interstellar and galactic origins. ACE's real-time solar wind observations are used for operational space weather forecasting by both NOAA's Space Weather Prediction Center and USAF because ACE can provide advance warning of geomagnetic storms that can overload power grids, disrupt communications on Earth, and present a hazard to astronauts.

AIM
Aeronomy of Ice in the Mesosphere

Launch Date: April 25, 2007
Phase: Extended Operations
Website: http://aim.hamptonu.edu/

AIM explores Polar Mesospheric Clouds (also called noctilucent clouds), Earth's highest clouds that form an icy membrane at the edge of the atmosphere, to find out why they form and why they are changing. In recent years, these clouds are being seen at lower latitudes more frequently. They are of special interest to scientists because the increased sightings may be related to climate change.

BARREL
Phase: Completed
Website: http://www.dartmouth.edu/~barrel/

BARREL is a balloon-based Mission of Opportunity to augment the measurements of NASA's Van Allen Probes spacecraft. BARREL consisted of two campaigns of five to eight long-duration balloons aloft in Antarctica simultaneously over a 1-month period that provided measurements of the precipitation of relativistic electrons from Earth's radiation belts.

CINDI/CNOFS
Coupled Ion-Neutral Dynamics Investigation

Launch Date: April 16, 2008
Phase: Extended Operations
Partner: USAF
Website: http://www.nasa.gov/cindi

The CINDI instrument suite improves our understanding of the dynamics of the Earth's ionosphere by studying the interactions between electrically neutral and electrically charged gases in the upper atmosphere. These interactions have a major influence on the structure of the ionosphere and can cause irregularities that result in disruptions in communications and navigation systems.

Cluster-II

Launch Date: July 16, 2000
Phase: Extended Operations
Partner: European Space Agency (ESA)
Website: http://sci.esa.int/cluster/

The ESA/NASA Cluster II mission is composed of four identical spacecraft flying in formation around Earth to study the impact of the Sun’s activity on the Earth’s space environment. This mission collects three-dimensional information on how the solar wind interacts with the magnetosphere and affects near-Earth space and its atmosphere, including aurorae.

Geotail

Launch Date: July 24, 1992
Phase: Extended Operations
Partner: Japan
Website: http://pwg.gsfc.nasa.gov/geotail.shtml

The JAXA/NASA Geotail mission studies the dynamics of the Earth’s magnetotail over a wide range of distances by measuring electric fields, magnetic fields, particles, and the waves traveling through the magnetostail.. Geotail’s orbit ensures that it often crossed the borders of the magnetosphere at varying points around Earth providing information on how Earth’s magnetic field interacts with the solar wind.

Hinode (Solar-B)

Launch Date: September 23, 2006
Phase: Extended Operations
Partner: Japan
Website: http://hinode.msfc.nasa.gov/

Hinode studies the generation, transport, and dissipation of magnetic energy from the photosphere to the corona to record how energy stored in the Sun's magnetic field is released, either gradually or violently, as the field rises into the Sun's outer atmosphere.

IBEX
Interstellar Boundary Explorer

Launch Date: October 19, 2008
Phase: Extended Operations
Partner: Switzerland
Website: http://ibex.swri.edu

IBEX measures energetic neutral atoms created at the boundary that separates our heliosphere from the local interstellar medium. It has provided the first evolving images of the heliosphere's outer edge and surroundings providing information on the nature of the interactions between the solar wind and the interstellar medium.

IRIS
Interface Region Imaging Spectrograph

Launch Date: June 27, 2013
Phase:
Prime Mission
Partner: Norway
Website: http://iris.lmsal.com

IRIS increases our understanding of energy transport into the corona and solar wind and provides an archetype for all stellar atmospheres by tracing the flow of energy and plasma through the chromosphere and transition region into the corona using spectroscopy and imaging.

RHESSI
Reuven Ramaty High Energy Solar Spectroscope Imager

Launch Date: February 5, 2002
Phase: Extended Operations
Website: http://hesperia.gsfc.nasa.gov/rhessi2

RHESSI advances our understanding of the basic physics of particle acceleration and explosive energy release in solar flares by imaging flares in X-rays and Gamma rays with fine angular and energy resolution to reveal the locations and spectra of the accelerated electrons and ions and of the hottest plasma.

SOHO
Solar and Heliospheric Observatory

Launch Date: December 2, 1995
Phase: Extended Operations
Partner: European Space Agency (ESA)
Website: http://sohowww.nascom.nasa.gov

The ESA/NASA SOHO mission studies the internal structure of the Sun, its extensive outer atmosphere and the origin of the solar wind and solar energetic particles. SOHO observations are used for space weather forecasting by NOAA's Space Weather Prediction Center. In addition to providing solar observations, SOHO data has been used by amateur astronomers to discover over 2,000 comets since its launch.

SDO
Solar Dynamics Observatory

Launch Date: February 11, 2010
Phase: Prime Mission
Website: http://sdo.gsfc.nasa.gov

SDO studies the Sun's dynamic behavior by measuring the solar interior, magnetic field, the hot plasma of the solar atmosphere,,and solar spectral irradiance. Solar variability causes changing conditions throughout interplanetary space, including near-Earth space, and can lead to disruptions in our technological infrastructure.

STEREO
Solar Terrestrial Relations Observatory

Launch Date: October 25, 2006
Phase: Extended Operations
Partners: France, Switzerland, United Kingdom, Germany, Belgium, DOD
Website: http://stereo.gsfc.nasa.gov

STEREO traces the flow of energy and matter from the Sun to Earth with two space-based observatories, and revealed the 3D structure of coronal mass ejections. STEREO real-time observations are used for space weather forecasting by NOAA's Space Weather Prediction Center. Since February 2011, the twin STEREO spacecraft have been providing scientists with unprecedented views of the far side of the Sun and are tracking the flow of solar material into interplanetary space.

THEMIS
Time History of Events and Macroscale Interactions during Substorms

Launch Date: February 17, 2007
Phase: Extended Operations
Partners: Canada, Germany, France and Austria
Website: http://themis.ssl.berkeley.edu/

THEMIS originally used five identically instrumented spacecraft to answer fundamental questions concerning the nature of the substorm instabilities that abruptly and explosively release solar wind energy stored within the Earth's magnetotail.

TIMED

Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics

Launch Date: December 7, 2001
Phase: Extended Operations
Website: http://www.timed.jhuapl.edu/

TIMED explores the Earth's Mesosphere and Lower Thermosphere (60–180 kilometers up) to understand the energy transfer into and out these regions and the basic structure that results from the energy transfer into the region. These regions are a gateway between Earth's environment and space, where the Sun's energy is first deposited into Earth's environment.

TWINS A & B
Two Wide-Angle Imaging Neutral-Atom Spectrometers

Launch Date: A-June 2006, B-March 13, 2008
Phase: Extended Operations
Partner: Germany, NRO
Website: http://twins.swri.edu/

TWINS enables the 3-dimensional visualization of large scale structures and dynamics within Earth's magnetosphere by imaging the charge exchange of neutral atoms over a broad energy range using two identical instruments on two widely spaced high-altitude, high-inclination spacecraft.

Van Allen Probes

Launch Date: August 30, 2012
Phase: Extended Operations
Partner: Czech Republic
Website: http://vanallenprobes.jhuapl.edu/

The Van Allen Probes use two identical spacecraft in elliptical orbits to provide an understanding, ideally to the point of predictability, of how populations of relativistic electrons and penetrating ions in space form or change in response to variable inputs of energy from the Sun. Van Allen Probes real-time beacon observations may be used for space weather forecasting.

Voyager Interstellar Mission
Launch Date: August and September 1977

Phase: Extended Operations
Website: http://voyager.jpl.nasa.gov/

The Voyager Interstellar Mission explores the outer heliosphere, heliosheath and now the interstellar medium with plasma, energetic particle, magnetic field and plasma wave instrumentation. Among them, the two Voyagers hold the records of the longest-operating and the most distant spacecraft.

Wind

Launch Date: November 1, 1994
Phase: Extended Operations
Partner: France
Website: http://wind.nasa.gov

Wind measures solar radio bursts, solar wind and energetic particle properties, and complements ACE observations from near the Lagrange 1 (L1) point. It also supports investigations of Gamma ray bursts in tandem with the Astrophysics SWIFT Gamma ray Explorer mission.

FUTURE MISSIONS

GOLD

Global-scale Observations of the Limb and Disk

Launch Date: 2017
Phase: Formulation
Web Site:

GOLD is a mission of opportunity that will fly an ultraviolet (UV) imaging spectrograph on a geostationary satellite designed to measure densities and temperatures in Earth's thermosphere and ionosphere. GOLD will perform unprecedented imaging of the weather of the upper atmosphere and examine the response of the upper atmosphere to forcing from the Sun, the magnetosphere and the lower atmosphere.

ICON

Ionospheric Connection Explorer

Launch Date: 2017
Phase: Formulation

Partners: Belgium
Web Site: http://icon.ssl.berkeley.edu/

ICON will explore the boundary between Earth and space – the ionosphere – to understand the physical connection between our ionosphere, lower atmosphere, and the immediate space environment around us. ICON will probe the extreme variability of Earth's ionosphere with *in situ* and remote-sensing instruments. Ionospheric fluctuations can interfere with or disrupt signals from communications and global positioning satellites.

LWS SET-1
Living With a Star Space Environment Testbed-1

Launch Date: Mid - 2016
Phase: Implementation
Partners: United Kingdom and France
Web site: http://lws-set.gsfc.nasa.gov

LWS-SET-1 will improve the engineering approach to accommodate and/or mitigate the effects of solar variability on spacecraft design and operations, and specifically demonstrate improved hardware performance in the space radiation environment.

MMS
Magnetospheric Multiscale

Launch Date: March 2015
Phase: Implementation
Frequency: S-band
Partners: Austria, France, Japan and Sweden
Web site: http://mms.gsfc.nasa.gov

MMS will solve the mystery of how magnetic fields around Earth connect and disconnect, explosively releasing energy via a process known as magnetic reconnection. MMS consists of four identical spacecraft that will provide the first three-dimensional views of this fundamental process that occurs throughout our universe.

Solar Orbiter Collaboration

Launch Date: 2017
Phase: Implementation
Partner: European Space Agency (ESA)-led
Web site: http://sci.esa.int/solarorbiter

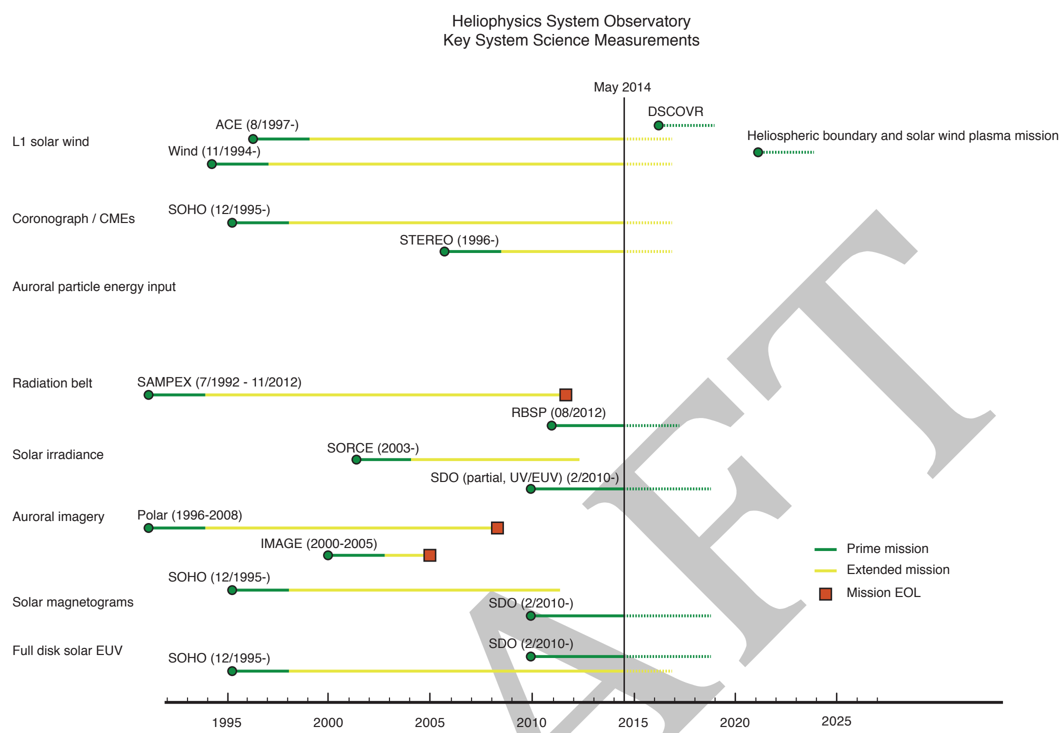
The Solar Orbiter mission will study the Sun from a distance closer than any previous spacecraft. This mission will characterize the Sun's polar regions and equatorial atmosphere and explore how fundamental plasma physical processes operate near the Sun. Solar Orbiter will take in-situ measurements of the solar wind plasma, fields, waves, and energetic particles along with remote sensing observations to identify the links between surface activity, the dynamic solar atmosphere., and the solar wind.

SPP
Solar Probe Plus

Launch Date: 2018
Phase: Implementation
Frequency: X-band, Ka-band
Partners: France, Germany, Belgium
Web site: http://solarprobe.jhuapl.edu/

The Solar Probe Plus will be a historic mission, flying into the Sun's atmosphere (or corona), for the first time. Solar Probe Plus will employ a combination of in-situ measurements and imaging to achieve the mission's primary scientific goal: to understand how the Sun's corona is heated and how the solar wind is accelerated. Solar Probe Plus will revolutionize our knowledge of the physics of the origin and evolution of the solar wind.

Appendix D: Key Science Measurements



Appendix E: ScienceTraceability Matrix

Roadmap RFA's	DS Challenges	Operating Missions	Missions in Development or Formulation
Understand magnetic reconnection	SH-3, SWMI-1	Wind, ACE, SOHO, RHESSI, Cluster, Hinode, STEREO, THEMIS, SDO, IRIS, Hinode, Geotail	MMS, SOC, SPP, MMS
Understand the plasma processes that accelerate and transport particles	SH-3, SH-4, SWMI-2	Wind, Geotail, ACE, SOHO, RHESSI, Cluster, TWINS, Hinode, STEREO, THEMIS/ARTEMIS, IBEX, SDO, Van Allen Probes, BARREL, IRIS, Voyager, IBEX	MMS, SOC, SPP
Understand ion-neutral interactions	SH-2, SH4, SWMI-3, AIMI-1, AIMI-2	TIMED, THEMIS, Cluster, Van Allen Probes, Voyager, IBEX, ACE, SOHO, SDO	GOLD, ICON, SPP
Understand the creation and variability of solar and stellar magnetic dynamos	SH-1	SOHO, Hinode, Wind, SDO, STEREO, IBEX, TIMED, AIM	SOC, SPP
Understand the role of turbulence and waves in the transport of mass, momentum, and energy	SH-2, SH4, SWMI-2, AIMI-3	TIMED, Hinode, Voyager, IBEX, Geotail, Cluster, TWINS	MMS, SPP
Understand the origin and dynamic evolution of solar plasmas and magnetic fields throughout the heliosphere	SH-1, SH-2, SH-3, SWMI-3, AIMI-4	SOHO, Hinode, Wind, SDO, STEREO, IBEX, TIMED, AIM, ACE, Voyager, Van Allen Probes	SOC, SPP
Understand the role of the Sun and its variability in driving change in the Earth's atmosphere, the space environment, and planetary objects	SWMI-3, AIMI-4	TIMED, AIM, ACE, Voyager, Van Allen Probes	SPP
Understand the coupling of the Earth's magnetosphere-ionosphere-atmosphere system, and its response to external and internal forcing	SWMI-3, SWMI-4, AIMI-1, AIMI-4	TIMED, AIM, Geotail, Cluster, TWINS, Cluster, THEMIS, Van Allen Probes	GOLD, ICON,
Understand the nature of the heliospheric boundary region, and the interactions between the solar wind and the local interstellar medium	SH-4	Voyager, IBEX	
Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers	SH-1, SH-3, SWMI-3, AIMI-4	SOHO, Hinode, Wind, SDO, STEREO, IBEX, TIMED, AIM, Van Allen Probes, IBEX, Voyager	SOC, SPP
Develop the capability to predict the origin, onset, and level of solar activity in order to identify potentially hazardous space weather events and all-clear intervals	SH-1, SH-3	SOHO, Hinode, Wind, SDO, STEREO, IBEX, TIMED, AIM	SOC, SPP
Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers	SH-3, SWMI-2, SWMI-3	Hinode, Wind, SDO, STEREO, IBEX, Geotail, Cluster, TWINS, Van Allen Probes	MMS, SOC, SPP
Understand, characterize, and model the space weather effects on and within terrestrial and planetary environments	SH-3, SWMI-2, SWMI-3, SWMI-4, AIMI-1, AIMI-2	TIMED, THEMIS, Cluster, VA Probes, Hinode, Wind, SDO, STEREO, IBEX, Geotail, Cluster, TWINS, Van Allen Probes	MMS, GOLD, ICON, SOC, SPP